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MAYNARD'S INDUSTRIAL ENGINEERING HANDBOOK

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SECTION 1

INDUSTRIAL ENGINEERING: PAST, PRESENT, AND FUTURE

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CHAPTER 1.1

THE PURPOSE AND EVOLUTION OF INDUSTRIAL ENGINEERING

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The historical events that led to the birth of industrial engineering provide significant insights into many of the principles that dominated its practice and development throughout the first half of the twentieth century. While these principles continue to impact the profession, many other conceptual and technological developments that currently shape and continue to mold the practice of the profession originated in the second half of the twentieth century. The objective of this chapter is to briefly summarize major events that have contributed to the birth and evolution of industrial engineering and assist in identifying common elements that continue to impact the purpose and objectives of the profession.

INTRODUCTION

Born in the late nineteenth century, industrial engineering is a dynamic profession whose growth has been fueled by the challenges and demands of manufacturing, government, and service organizations throughout the twentieth century. It is also a profession whose future depends not only on the ability of its practitioners to react to and facilitate operational and organizational change but, more important, on their ability to anticipate, and therefore lead, the change process itself.

The historical events that led to the birth of industrial engineering provide significant insights into many of the principles that dominated its practice and development throughout the first half of the twentieth century. While these principles continue to impact the profession, many of the conceptual and technological developments that currently shape and will continue to mold the practice of the profession originated in the second half of the twentieth century. The objective of this chapter is to briefly summarize the evolution of industrial engineering and in so doing assist in identifying those common elements that define the purpose and objectives of the profession. We hope that the reader will be sufficiently interested in the historical events to pursue more comprehensive and basic sources including Emerson and Naehring [1], Saunders [2], Shultz [3], Nadler [4], Pritsker [5], and Turner et al. [6]. Since the history of industrial engineering is strongly linked to the history of manufacturing, the reader is also advised to refer to Hopp and Spearman [7] for a particularly interesting and relevant exposition of the history of American manufacturing. This chapter draws heavily on these works and their references.

EARLY ORIGINS

Before entering into the history of the profession, it is important to note that the birth and evolution of industrial engineering are analogous to those of its engineering predecessors. Even though there are centuries-old examples of early engineering practice and accomplishments, such as the Pyramids, the Great Wall of China, and the Roman construction projects, it was not until the eighteenth century that the first engineering schools appeared in France. The need for greater efficiency in the design and analysis of bridges, roads, and buildings resulted in principles of early engineering concerned primarily with these topics being taught first in military academies (*military engineering*). The application of these principles to nonmilitary or civilian endeavors led to the term *civil engineering.* Interrelated advancements in the fields of physics and mathematics laid the groundwork for the development and application of mechanical principles. The need for improvements in the design and analysis of materials and devices such as pumps and engines resulted in the emergence of *mechanical engineering* as a distinct field in the early nineteenth century. Similar circumstances, albeit for different technologies, can be ascribed to the emergence and development of *electrical engineering* and *chemical engineering.* As has been the case with all these fields, *industrial engineering* developed initially from empirical evidence and understanding and then from research to develop a more scientific base.

The Industrial Revolution

Even though historians of science and technology continue to argue about when industrial engineering began, there is a general consensus that the empirical roots of the profession date back to the Industrial Revolution, which began in England during the mideighteenth century. The events of this era dramatically changed manufacturing practices and served as the genesis for many concepts that influenced the scientific birth of the field a century later. The driving forces behind these developments were the technological innovations that helped mechanize many traditional manual operations in the textile industry. These include the flying shuttle developed by John Kay in 1733, the spinning jenny invented by James Hargreaves in 1765, and the water frame developed by Richard Arkwright in 1769. Perhaps the most important innovation, however, was the steam engine developed by James Watt in 1765. By making steam practical as a power source for a host of applications, Watt's invention freed manufacturers from their reliance on waterpower, opening up far greater freedom of location and industrial organization. It also provided cheaper power, which led to lower production costs, lower prices, and greatly expanded markets. By facilitating the substitution of capital for labor, these innovations generated economies of scale that made mass production in centralized locations attractive for the first time. The concept of a production system, which lies at the core of modern industrial engineering practice and research, had its genesis in the factories created as a result of these innovations.

Specialization of Labor

The concepts presented by Adam Smith in his treatise *The Wealth of Nations* also lie at the foundation of what eventually became the theory and practice of industrial engineering. His writings on concepts such as the division of labor and the "invisible hand" of capitalism served to motivate many of the technological innovators of the Industrial Revolution to establish and implement factory systems. Examples of these developments include Arkwright's implementation of management control systems to regulate production and the output of factory workers, and the well-organized factory that Watt, together with an associate, Matthew Boulton, built to produce steam engines. The efforts of Watt and Boulton and their sons led to the planning and establishment of the first integrated machine manufacturing facility in the world, including the implementation of concepts such as a cost control system designed to decrease waste and improve productivity and the institution of skills training for craftsmen. Many features of life in the twentieth century including widespread employment in large-scale factories, mass production of inexpensive goods, the rise of big business, and the existence of a professional manager class are a direct consequence of the contributions of Smith and Watt.

Another early contributor to concepts that eventually became associated with industrial engineering was Charles Babbage. The findings that he made as a result of visits to factories in England and the United States in the early 1800s were documented in his book entitled *On the Economy of Machinery and Manufacturers.* The book includes subjects such as the time required for learning a particular task, the effects of subdividing tasks into smaller and less detailed elements, the time and cost savings associated with changing from one task to another, and the advantages to be gained by repetitive tasks. In his classic example on the manufacture of straight pins, Babbage extends the work of Adam Smith on the division of labor by showing that money could be saved by assigning lesser-paid workers (in those days women and children) to lesser-skilled operations and restricting the higher-skilled, higher-paid workers to only those operations requiring higher skill levels. Babbage also discusses notions related to wage payments, issues related to present-day profit sharing plans, and even ideas associated with the organization of labor and labor relations. It is important to note, however, that even though much of Babbage's work represented a departure from conventional wisdom in the early nineteenth century, he restricted his work to that of observing and did not try to improve the methods of making the product, to reduce the times required, or to set standards of what the times should be.

Interchangeability of Parts

Another key development in the history of industrial engineering was the concept of interchangeable parts. The feasibility of the concept as a sound industrial practice was proven through the efforts of Eli Whitney and Simeon North in the manufacture of muskets and pistols for the U.S. government. Prior to the innovation of interchangeable parts, the making of a product was carried out in its entirety by an artisan, who fabricated and fitted each required piece. Under Whitney's system, the individual parts were mass-produced to tolerances tight enough to enable their use in any finished product. The division of labor called for by Adam Smith could now be carried out to an extent never before achievable, with individual workers producing single parts rather than completed products. The result was a significant reduction in the need for specialized skills on the part of the workers—a result that eventually led to the industrial environment, which became the object of study of Frederick W. Taylor.

PIONEERS OF INDUSTRIAL ENGINEERING

Taylor and Scientific Management

While Frederick W. Taylor did not use the term *industrial engineering* in his work, his writings and talks are generally credited as being the beginning of the discipline. One cannot presume to be well versed in the origins of industrial engineering without reading Taylor's books: *Shop Management* and *The Principles of Scientific Management.* An engineer to the core, he earned a degree in mechanical engineering from Stevens Institute of Technology and developed several inventions for which he received patents. While his engineering accomplishments would have been sufficient to guarantee him a place in history, it was his contributions to management that resulted in a set of principles and concepts considered by Drucker to be "possibly the most powerful as well as lasting contribution America has made to Western thought since the Federalist Papers."

The core of Taylor's system consisted of breaking down the production process into its component parts and improving the efficiency of each. Paying little attention to rules of thumb and standard practices, he honed manual tasks to maximum efficiency by examining each component separately and eliminating all false, slow, and useless movements. Mechanical work was accelerated through the use of jigs, fixtures, and other devices—many invented by Taylor himself. In essence, Taylor was trying to do for work units what Whitney had done for material units: standardize them and make them interchangeable.

Improvement of work efficiency under the Taylor system was based on the analysis and improvement of work methods, reduction of the time required to carry out the work, and the development of work standards. With an abiding faith in the scientific method, Taylor's contribution to the development of "time study" was his way of seeking the same level of predictability and precision for manual tasks that he had achieved with his formulas for metal cutting.

Taylor's interest in what today we classify as the area of work measurement was also motivated by the information that studies of this nature could supply for planning activities. In this sense, his work laid the foundation for a broader "science of planning": a science totally empirical in nature but one that he was able to demonstrate could significantly improve productivity. To Taylor, scientific management was a philosophy based not only on the scientific study of work but also on the scientific selection, education, and development of workers.

His classic experiments in shoveling coal, which he initiated at the Bethlehem Steel Corporation in 1898, not only resulted in development of standards and methods for carrying out this task, but also led to the creation of tool and storage rooms as service departments, the development of inventory and ordering systems, the creation of personnel departments for worker selection, the creation of training departments to instruct workers in the standard methods, recognition of the importance of the layout of manufacturing facilities to ensure minimum movement of people and materials, the creation of departments for organizing and planning production, and the development of incentive payment systems to reward those workers able to exceed standard outputs. Any doubt about Taylor's impact on the birth and development of industrial engineering should be erased by simply correlating the previously described functions with many of the fields of work and topics that continue to play a major role in the practice of the profession and its educational content at the university level.

Frank and Lillian Gilbreth

The other cornerstone of the early days of industrial engineering was provided by the husband and wife team of Frank and Lillian Gilbreth. Consumed by a similar passion for efficiency, Frank Gilbreth's application of the scientific method to the laying of bricks produced results that were as revolutionary as those of Taylor's shoveling experiment. He and Lillian extended the concepts of scientific management to the identification, analysis, and measurement of fundamental motions involved in performing work. By applying the motion-picture camera to the task of analyzing motions they were able to categorize the elements of human motions into 18 basic elements or *therbligs.* This development marked a distinct step forward in the analysis of human work, for the first time permitting analysts to design jobs with knowledge of the time required to perform the job. In many respects these developments also marked the beginning of the much broader field of human factors or ergonomics.

While their work together stimulated much research and activity in the field of motion study, it was Lillian who also provided significant insight and contributions to the human issues associated with their studies. Lillian's book, *The Psychology of Management* (based on her doctoral thesis in psychology at Brown University), advanced the premise that because of its emphasis on scientific selection and training, scientific management offered ample opportunity for individual development, while traditional management stifled such development by concentrating power in a central figure. Known as the "first lady of engineering," she was the first woman to be elected to the National Academy of Engineering and is generally credited with bringing to the industrial engineering profession a concern for human welfare and human relations that was not present in the work of many pioneers of the scientific management movement.

Other Pioneers

In 1912, the originators and early pioneers, the first educators and consultants, and the managers and representatives of the first industries to adopt the concepts developed by Taylor and Gilbreth gathered at the annual meeting of the American Society of Mechanical Engineers (ASME) in New York City. The all-day session on Friday, December 6, 1912, began with a presentation titled "The Present State of the Art of Industrial Management." This report and the subsequent discussions provide insight and understanding about the origin and relative contributions of the individuals involved in the birth of a unique new profession: industrial engineering.

In addition to Taylor and Gilbreth, other pioneers present at this meeting included Henry Towne and Henry Gantt. Towne, who was associated with the Yale and Towne Manufacturing Company, used ASME as the professional society to which he presented his views on the need for a professional group with interest in the problems of manufacturing and management. This suggestion ultimately led to the creation of the Management Division of ASME, one of the groups active today in promoting and disseminating information about the art and science of management, including many of the topics and ideas industrial engineers are engaged in. Towne was also concerned with the economic aspects and responsibilities of the engineer's job including the development of wage payment plans and the remuneration of workers. His work and that of Frederick Halsey, father of the Halsey premium plan of wage payment, advanced the notion that some of the gains realized from productivity increases should be shared with the workers creating them.

Gantt's ideas covered a wider range than some of his predecessors. He was interested not only in standards and costs but also in the proper selection and training of workers and in the development of incentive plans to reward them. Although Gantt was considered by Taylor to be a true disciple, his disagreements with Taylor on several points led to the development of a "task work with bonus" system instead of Taylor's "differential piece rate" system and explicit procedures for enabling workers to either protest or revise standards. He was also interested in scheduling problems and is best remembered for devising the Gantt chart: a systematic graphical procedure for planning and scheduling activities that is still widely used in project management.

In attendance were also the profession's first educators including Hugo Diemer, who started the first continuing curriculum in industrial engineering at Pennsylvania State College in 1908; William Kent, who organized an industrial engineering curriculum at Syracuse University in the same year; Dexter Kimball, who presented an academic course in works administration at Cornell University in 1904; and C. Bertrand Thompson, an instructor in industrial organization at Harvard, where the teaching of Taylor's concepts had been implemented. Consultants and industrial managers at the meeting included Carl Barth, Taylor's mathematician and developer of special purpose slide rules for metal cutting; John Aldrich of the New England Butt Company, who presented the first public statement and films about micromotion study; James Dodge, president of the Link-Belt Company; and Henry Kendall, who spoke of experiments in organizing personnel functions as part of scientific management in industry. Two editors present were Charles Going of the *Engineering Magazine* and Robert Kent, editor of the first magazine with the title of *Industrial Engineering.* Lillian Gilbreth was perhaps the only pioneer absent since at that time women were not admitted to ASME meetings.

Another early pioneer was Harrington Emerson. Emerson became a champion of efficiency independent of Taylor and summarized his approach in his book, the *Twelve Principles* *of Efficiency.* These principles, which somewhat paralleled Taylor's teachings, were derived primarily through his work in the railroad industry. Emerson, who had reorganized the workshops of the Santa Fe Railroad, testified during the hearings of the Interstate Commerce Commission concerning a proposed railroad rate hike in 1910 to 1911 that scientific management could save "a million dollars a day." Because he was the only "efficiency engineer" with firsthand experience in the railroad industry, his statement carried enormous weight and served to emblazon scientific management on the national consciousness. Later in his career he became particularly interested in selection and training of employees and is also credited with originating the term *dispatching* in reference to shop floor control, a phrase that undoubtedly derives from his railroad experience.

THE POST–WORLD WAR I ERA

By the end of World War I, scientific management had firmly taken hold. Large-scale, vertically integrated organizations making use of mass production techniques were the norm. Application of these principles resulted in spectacular increases in production. Unfortunately, however, because increases in production were easy to achieve, management interest was focused primarily on the implementation of standards and incentive plans, and little attention was paid to the importance of good methods in production. The reaction of workers and the public to unscrupulous management practices such as "rate cutting" and other speedup tactics, combined with concerns about dehumanizing aspects of the application of scientific management, eventually led to legislation limiting the use of time standards in government operations.

Methods Engineering and Work Simplification

These reactions led to an increased interest in the work of the Gilbreths. Their efforts in methods analysis, which had previously been considered rather theoretical and impractical, became the foundation for the resurgence of industrial engineering in the 1920s and 1930s. In 1927, H. B. Maynard, G. J. Stegmerten, and S. M. Lowry wrote *Time and Motion Study,* emphasizing the importance of motion study and good methods. This eventually led to the term *methods engineering* as the descriptor of a technique emphasizing the "elimination of every unnecessary operation" prior to the determination of a time standard. In 1932, A. H. Mogensen published *Common Sense Applied to Time and Motion Study,* in which he stressed the concepts of motion study through an approach he chose to call *work simplification.* His thesis was simply that the people who know any job best are the workers doing that job. Therefore, if the workers are trained in the steps necessary to analyze and challenge the work they are doing, then they are also the ones most likely to implement improvements. His approach was to train key people in manufacturing plants at his Lake Placid Work Simplification Conferences so that they could in turn conduct similar training in their own plants for managers and workers. This concept of taking motion study training directly to the workers through the work simplification programs was a tremendous boon to the war production effort during World War II. The first Ph.D. granted in the United States in the field of industrial engineering was also the result of research done in the area of motion study. It was awarded to Ralph M. Barnes by Cornell University in 1933 and was supervised by Dexter Kimball. Barnes's thesis was rewritten and published as *Motion and Time Study:* the first full-length book devoted to this subject. The book also attempted to bridge the growing chasm between advocates of time study versus motion study by emphasizing the inseparability of these concepts as a basic principle of industrial engineering.

Another result of the reaction was a closer look at the behavioral aspects associated with the workplace and the human element. Even though the approach taken by Taylor and his fol-

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lowers failed to appreciate the psychological issues associated with worker motivation, their work served to catalyze the behavioral approach to management by systematically raising questions on authority, motivation, and training. The earliest writers in the field of industrial psychology acknowledged their debt to scientific management and framed their discussions in terms consistent with this system.

The Hawthorne Experiment

A major episode in the quest to understand behavioral aspects was the series of studies conducted at the Western Electric Hawthorne plant in Chicago between 1924 and 1932. These studies originally began with a simple question: How does workplace illumination affect worker productivity? Under sponsorship from the National Academy of Science, a team of researchers from the Massachusetts Institute of Technology (MIT) observed groups of coil-winding operators under different lighting levels. They observed that productivity relative to a control group went up as illumination increased, as had been expected. Then, in another experiment, they observed that productivity also increased when illumination *decreased,* even to the level of moonlight. Unable to explain the results, the original team abandoned the illumination studies and began other tests on the effect of rest periods, length of work week, incentive plans, free lunches, and supervisory styles on productivity. In most cases the trend was for higher than normal output by the groups under study.

Approaching the problem from the perspective of the "psychology of the total situation," experts brought in to study the problem came to the conclusion that the results were primarily due to "a remarkable change in the mental attitude in the group." Interpretations of the study were eventually reduced to the simple explanation that productivity increased as a result of the attention received by the workers under study. This was dubbed the *Hawthorne effect.* However, in subsequent writings this simple explanation was modified to include the argument that work is a group activity and that workers strive for a sense of belonging—not simple financial gain—in their jobs. By emphasizing the need for listening and counseling by managers to improve worker collaboration, the industrial psychology movement shifted the emphasis of management from technical efficiency—the focus of Taylorism—to a richer, more complex, human-relations orientation.

Other Contributions

Many other individuals and events should be recorded in any detailed history of the beginnings of industrial engineering. Other names that should be included in any library search, which will lead to other contributors, include L. P. Alford, Arthur C. Anderson, W. Edwards Deming, Eugene L. Grant, Robert Hoxie, Joseph Juran, Marvin E. Mundel, George H. Shepard, and Walter Shewart. In particular, Shewart's book, *Economic Control of the Quality of Manufactured Product,* published in 1931, contains over 20 years of work on the theory of sampling as an effective approach for controlling quality in the production process. While many of his ideas were not applied until after World War II, his work marked the beginning of modern statistical quality control and the use of many of the tools that today are taught to everyone, including workers, as a means of empowering them to control the quality of their work.

Status at the End of This Era

In 1943, the Work Standardization Committee of the Management Division of ASME included under the term *industrial engineering* functions such as budgets and cost control, manufacturing engineering, systems and procedures management, organization analysis, and wage and salary administration. Most of the detailed activities were primarily related to the task of methods development and analysis and the development of time standards, although other activities such as plant layout and materials handling, and the production control activities of routing and scheduling, were also contained in this definition. The level of coverage of these topics varied significantly among manufacturing organizations, and from an organizational standpoint, the activities might have been found within the engineering department, as part of manufacturing, or in personnel. From an educational perspective, many of the methodologies and techniques taught in the classroom and laboratories were very practical and largely empirically derived. Sophisticated mathematical and computing methods had not yet been developed, and further refinement and application of the scientific approach to problems addressed by industrial engineers was extremely difficult. Like other professional areas, the start of industrial engineering was rough, empirical, qualitative, and, to a great extent, dependent on the commitment and charisma of the pioneers to eloquently carry the day. The net effect of all this was that industrial engineering, at the end of this era, was still a dispersed discipline with no centralized focus and no national organization to bring it together. This situation started to change shortly after World War II.

THE POST–WORLD WAR II ERA

In 1948, the American Institute of Industrial Engineers (AIIE) was founded in Columbus, Ohio. The requirements for membership included either the completion of a college-level program or equivalent breadth and understanding as derived from engineering experience. The American Society for Quality Control was also founded at the close of World War II. The establishment of these two societies requiring professional credentials for membership began to provide the focus that had been lacking in the profession to that time. These developments, along with the emergence of a more quantitative approach to the issues of industrial engineering, provided the impetus for the significant transition that the discipline experienced during this era.

The Emergence of Operations Research

During World War II and the balance of the 1940s, developments of crucial importance to the field occurred. The methods used by the industrial engineer, including statistical analysis, project management techniques, and various network-based and graphical means of analyzing very complex systems, were found to be very useful in planning military operations. Under the pressure of wartime, many highly trained scientists from a broad range of disciplines contributed to the development of new techniques and devices, which led to significant advances in the modeling, analysis, and general understanding of operational problems. Their approach to the complex problems they faced became known as *operations research.* Similarities between military operational problems and the operational problems of producing and distributing goods led some of the operations researchers from wartime to extend their area of activity to include industrial problems. This resulted in considerable interaction between industrial engineers and members of other scientific disciplines and in an infusion of new ideas and approaches to problem solving that dramatically impacted the scope of industrial engineering education and practice.

The decade of the 1950s marked the transition of industrial engineering from its prewar empirical roots to an era of quantitative methods. The transition was most dramatic in the educational sector where research in industrial engineering began to be influenced by the mathematical underpinnings of operations research and the promise that these techniques provided for achieving the optimal strategy to follow for a production or marketing situation.

While the application of operations research concepts and techniques was also pursued by practicing industrial engineers and others, the gap between theoretical research in universities and actual applications in government and industry was still quite great during those years.

The practice of industrial engineering during the 1950s continued to draw heavily from the foundation concepts of work measurement, although the emergence of a greater scientific base for industrial engineering also influenced this area. A significant development that gained prominence during these years was predetermined motion time systems. While both Taylor and Gilbreth had essentially predicted this development, it was not until the development of *work factor* by a research team from RCA and MTM (methods time measurement) by Maynard and Associates that the vision of these two pioneers was converted into industry-usable tools for what was still the most basic of industrial engineering functions.

By the 1960s, however, methodologies such as linear programming, queuing theory, simulation, and other mathematically based decision analysis techniques had become part of the industrial engineering educational mainstream. Operations research now provided the industrial engineer with the capability to mathematically model and better understand the behavior of large problems and systems. However, it was the development of the digital computer and the high-speed calculation and storage capabilities provided by this device that provided the industrial engineer with the opportunity to model, design, analyze, and essentially experiment with large systems. The ability to experiment with large systems also placed industrial engineers on a more equal footing with their engineering counterparts. Other engineers were generally not limited in their ability to experiment prior to the computer age because they could build small-scale models or pilot plants that enabled them to extrapolate the results to a full-scale system. However, prior to the development of the digital computer, it was practically impossible for the industrial engineer to experiment with large-scale manufacturing and production systems without literally obstructing the capabilities of the facility under study.

These developments essentially changed industrial engineering from a field primarily concerned with the individual human task performed in a manufacturing setting to a field concerned with improving the performance of human organizations. They also ushered in an era where the scope of application of industrial engineering grew to include numerous service operations such as hospitals, airlines, financial institutions, educational institutions, and other civilian and nongovernmental institutions.

A Definition of Industrial Engineering

Recognition of this new role and the breadth of the field were reflected in the definition of industrial engineering that was adopted by the American Institute of Industrial Engineers in the early 1960s:

> Industrial engineering is concerned with the design, improvement, and installation of integrated systems of men, materials, equipment and energy. It draws upon specialized knowledge and skill in the mathematical, physical and social sciences together with the principles and methods of engineering analysis and design to specify, predict, and evaluate the results to be obtained from such systems.

Status at the End of This Era

The decades of the 1960s and 1970s are considered by many to constitute the second phase in the history of industrial engineering during the twentieth century. During these years the field became modeling-oriented, relying heavily on mathematics and computer analysis for its development. In many respects, industrial engineering was advancing along a very appropriate path, substituting many of the more subjective and qualitative aspects of its early years with more quantitative, science-based tools and techniques. This focus was also consistent with the prevalent mind-set of the times that emphasized acquisition of hard facts, precise measurements, and objective approaches for the modeling and analysis of human organizations and systems. While some inroads were made in the area of human and organizational behavior, particularly in the adoption of human factors or ergonomics concepts for the design and improvement of integrated work systems, industrial engineers during this era tended to focus primarily on the development of quantitative and computational tools almost to the exclusion of any other concerns.

Evolution of the IE Job Function

Figure 1.1.1 illustrates how the job functions of industrial engineers (IEs) changed in the 1960s and 1970s [5]. Activities throughout the early part of the 1960s were still concerned primarily with work simplification and methods improvement, plant layout, and direct labor standards. In the next five years, work began on indirect labor standards and project engineering. During the 1970s, quantitative approaches and computer modeling caused a dramatic shift in job functions. By the end of the 1970s, over 70 percent of industrial engineering job functions were estimated to be in the areas of scientific inventory management, systematic design and analysis, and project engineering.

The evolutionary trends illustrated by Fig. 1.1.1 reflected a future where the fraction of workers in direct labor positions would continue to decrease and the number of positions in the service industries would increase. These changes, along with increased information processing capabilities, pointed toward a future where industrial engineering functions and roles would provide input and impact the decision and planning processes of management at higher levels than ever before.

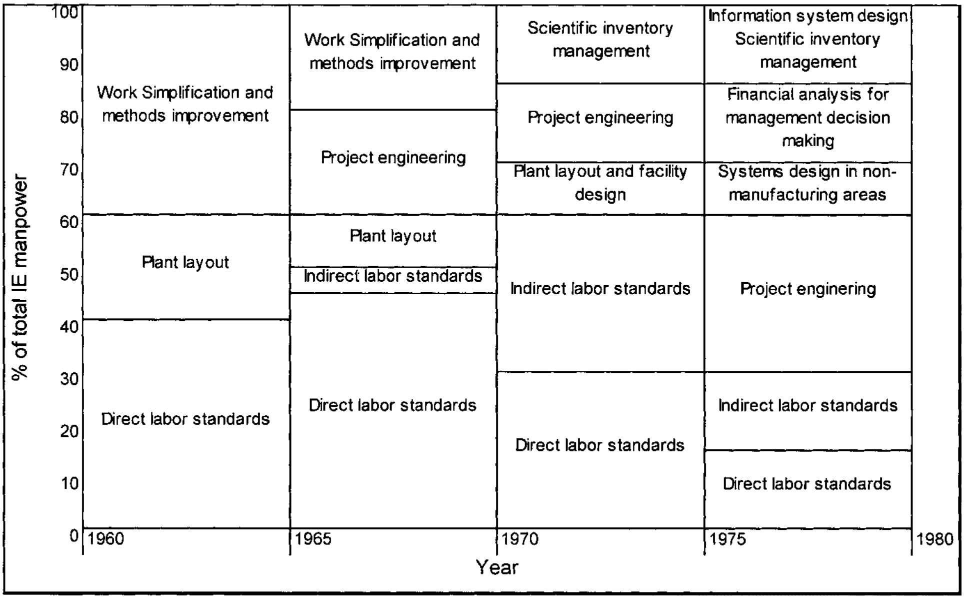

FIGURE 1.1.1 Changes in the IE function between 1960 and 1980. (*From A.A.B. Pritsker,* Papers, Experiences, Perspectives *[5].*)

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THE ERA FROM 1980 TO 2000

The 1980s in many ways validated these projections. During this decade the role of the industrial engineer expanded significantly beyond its traditional support functions to include organizational leadership responsibilities in both the *design* and *integration* of manufacturing and service systems. In the case of manufacturing, these functions oftentimes included the design and development of new hardware and software that enabled the automation of many production and support functions and the integration of these functions within operational environments.

With many manufacturing environments now consisting of complex arrays of computerized machines, the design and integration of information systems that could effectively control and handle data related to product designs, materials, parts inventories, work orders, production schedules, and engineering designs became a growing element in the role of the industrial engineer. The automatic generation of process plans, bills of materials, tool release orders, work schedules, and operator instructions; the growth in numerically controlled machine tool capability; and the use of robots in a variety of industrial settings are examples of applications in which industrial engineering played a major role during the 1980s. Many of these functions, which include tasks critical to the success of computer-aided design (CAD), computer-aided manufacturing (CAM), or computer-integrated manufacturing (CIM) efforts, reflected the broadening, systems-related role of the industrial engineer in many manufacturing organizations.

Sophisticated tools with which to analyze problems and design systems, which by now had become part of the industrial engineering toolkit, were also applied successfully in service activities such as airline reservation systems, telephone systems, financial systems, health systems, and many other nonmanufacturing environments. Many of these developments were a natural outgrowth of the emphasis on quantitative and computational tools that had impacted the profession during the prior two decades. While a number of these applications also reflected a growing role in design and integration functions, a major impact of the field on the service sector was the creation of a growing appreciation of the more generic nature of the term *production systems* to include the provision of services and the value of the role of industrial engineering in these environments. In addition to assuming increasingly higher-level managerial responsibilities in both manufacturing and service organizations, the roles of industrial engineers expanded to include functions such as software developer, consultant, and entrepreneur. The broad preparation of the industrial engineer, combined with the technological developments of this decade, had apparently resulted in a profession and a legion of professionals uniquely qualified to play the integrative, systems-oriented role that was now required to enhance the effectiveness of organizations.

The New Challenges of This Era

Despite indications that seemed to point to a profession that was moving in the right direction, many of these same organizations that industrial engineers were serving found themselves losing ground during the 1980s to non-U.S. competitors. This was particularly true in major industrial arenas such as the automobile industry, machine tooling, and many sectors of the electronics industry. While it would certainly be an overstatement to blame these developments on industrial engineering (it could be argued that part of the problem was that many industrial engineers had still not been able to influence managerial decision making in many of these industries at high enough levels), a relevant and related question was whether the high degree of specialization that resulted from many industrial engineering efforts during this decade had created a field that placed more emphasis on tools and techniques than the problems it was intending to solve. This perception was reinforced by studies that indicated that many of the non-U.S. competitors that had made significant gains on U.S. organizations were accomplishing their gains by focusing not so much on tools and techniques, but rather on questioning the underlying premises associated with basic issues and problems in the areas of quality, productivity, timeliness, flexibility, responsiveness to customers, and cost minimization.

What many have concluded was that even though the industrial engineering profession seemed to be moving in the right direction from the post World War II years through the early 1980s, the actual impact of this effort was off the mark. Rather than continuing to question prevailing modes of reasoning related to the organization of work and management, as had been done by the pioneers of the profession, the argument is that the field reached a point where industrial engineers became more concerned with finding places to apply the many new tools and techniques that had been developed and less concerned with addressing the needs and problems of the organizations they were serving. While there is undoubtedly a large amount of truth in this assertion, it is also the natural result of a profession that was striving to enhance its respectability through the incorporation of a more "scientific" approach to its problem-solving efforts, an approach that is also consistent with the intent of the pioneers of the profession. The net result of these developments, which essentially came to a head in the mid-1980s, was a profession at the crossroads. It was at this point that the industrial engineering profession started what is essentially the third phase of its development, a period of reassessment, self-study, and growth that continues as we enter the twenty-first century.

One of the leading causes of the reassessment process that industrial engineering started experiencing in the mid-1980s was the dramatic results obtained by Japanese organizations such as Toyota, Sony, and others that questioned many of the underlying manufacturing systems and management practices associated with the areas of quality and timeliness. Their commitment to the application of quality management principles, which they were first exposed to as early as the 1950s by Deming and others, resulted in product quality levels and customer expectations that were significantly higher than those obtained by their U.S. counterparts. Similar results were obtained through the commitment of significant resources to the training of their workforce for over two decades in principles of work simplification, which led to the development of manufacturing management philosophies such as just-in-time production and the eventual implementation of many of the principles we today associate with *continuous improvement* methodologies.

One of the most important lessons learned by these developments, from an industrial engineering perspective, was that the Japanese were able to illustrate very dramatically that the continued development of more sophisticated quality control techniques or inventory models did not necessarily lead, in practice, to greater organizational productivity. It was the questioning of the underlying assumptions associated with techniques used to determine acceptable quality limits, production cycle times, economic order quantities, and other related concepts that lay at the heart of the issue of organizational productivity, at least in most manufacturing environments. The wake-up call provided by these and similar developments, while painful at first, have eventually led to a process of change in both the focus and role of the industrial engineer that is serving the profession well as it begins the next century.

Evolution of the Role of the IE During This Era

The growing role played by industrial engineers as manufacturing systems integrators and the paradigm shifts that many industrial engineers have stimulated in the development of new manufacturing technologies serve as examples of this new focus in manufacturing environments. In the 1980s, the problem of using excessive technologies without proper integration led to the creation of many "islands of automation," or situations where various parts of a factory automated by computers, robots, and flexible machines did not result in a productive environment because of a lack of integration among the components. A greater focus on systems integration has yielded more organizations whose functions are mutually rationalized and coordinated through appropriate levels of computers in conjunction with information and communication technologies. The role played by industrial engineers during the 1990s in these efforts includes not only the integration of shop floor activities and islands of automation, but also a greater emphasis on shortened development and manufacturing lead times, knowledge sharing, distributed decision making and coordination, integration of manufacturing decision processes, enterprise integration, and coordination of manufacturing activities with external environments. The impact of the industrial engineer in new manufacturing technologies can also be illustrated through the field's growing role in the development and application of concepts such as flexible, agile, and intelligent manufacturing systems and processes; design techniques and criteria for manufacturing, assembly, and concurrent engineering; rapid prototyping and tooling; and operational modeling including very significant contributions in factory simulation and integrated modeling capabilities [9,10].

Similar statements can be made for the impact of industrial engineering in government and service sectors where the catalyst has been a renewed focus on process modeling, analysis, and improvement, and the development and application of operational modeling and optimization-based approaches. Sectors where the industrial engineer is playing an increasingly active role include financial services, both in new product development and process improvement; distribution and logistics services, particularly through the development of new software and operational modeling, analysis, and design capabilities; government services; and many segments of the growing worldwide market for information services and technologies.

Figure 1.1.2 illustrates a projection for future IE roles as presented by Pritsker in 1985 [5]. This projection was based on the premise that the conceptual framework for an industrial engineer parallels the framework for decision makers in general, thereby allowing future roles to be categorized as those associated with strategic planning, management control, or operational control. Strategic planning was defined as the process of deciding on the objectives of an organization, on changes in these objectives, on the resources used to obtain these objectives, and on the policies that are to govern the acquisition, use, and disposition of

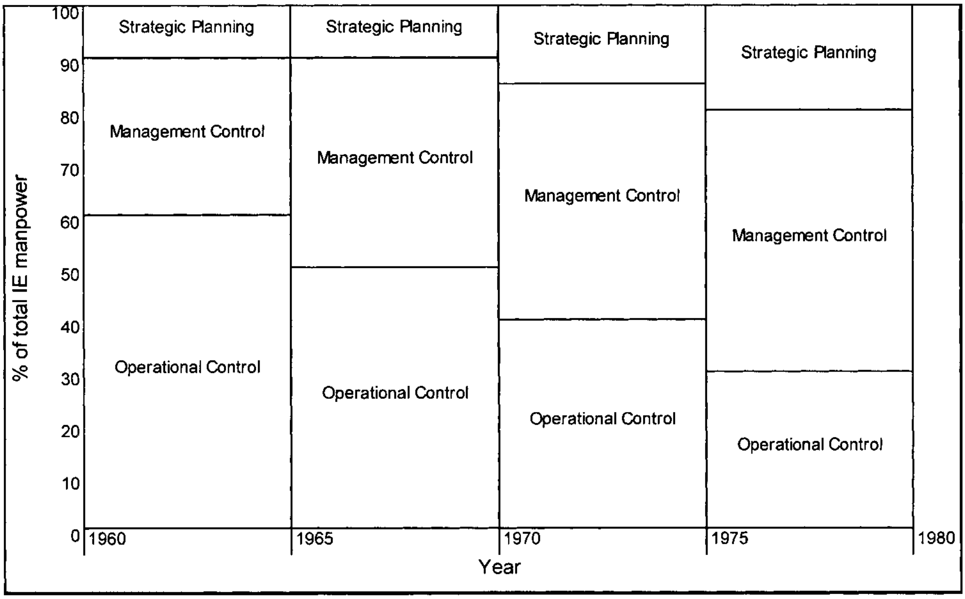

FIGURE 1.1.2 Changes in the IE function between 1960 and 1980. (*From A.A.B. Pritsker,* Papers, Experiences, Perspectives *[5].*)

resources. Management control was defined as the process by which managers assure that the required resources are obtained and used effectively and efficiently in the accomplishment of the organization's objectives. Operational control refers to the process of assuring that specific tasks are carried out effectively and efficiently.

The projection called for industrial engineers to increase their role in the strategic planning and management control areas and to lessen their involvement in the area of operational control. The rationale for this projected trend was based on the following observations [5]:

1. That operational control including data acquisition would become more automated. This would result in a growing role for the industrial engineer in the development of tools and procedures for providing this automation to companies, a role that falls in the category of management control systems since it would involve the design and development of both hardware and software.
2. That strategic planning, including entrepreneurship, would continue to increase during the latter part of the 1980s and throughout the decade of the 1990s with industrial engineers building and using models of the system and the corporation.

While it would be difficult to determine if the percentages of this projection have been borne out, there should be no doubt that the projected trend has indeed accurately reflected the role of the industrial engineer as we enter the twenty-first century. Regardless of the many job titles that industrial engineers may hold at this moment, their role, either within manufacturing, service, government, and educational organizations or as the pilots of their own organizations, has moved significantly from the operational control origins of the profession to a role that is influencing not only the accomplishment of organizational objectives but, even more so, the decisions related to defining organizational objectives and policies. The industrial engineer as a systems designer, software developer, systems integrator, entrepreneur, consultant, and/or manager is now a commonplace occurrence and reflects the growing maturity of this vibrant and dynamic profession.

FUTURE CHALLENGES AND OPPORTUNITIES

Emerging economies, social and political transitions, and new ways of doing business are changing the world dramatically. These trends suggest that the competitive environment for the practice of industrial engineering in the near future will be significantly different than it is today. While the industrial engineering profession and the role of the IE has changed significantly over the last 20 years, the emergence of new technologies, spurred by intense competition, will continue to lead to dramatically new products and processes both in manufacturing and service environments. New management and labor practices, organizational structures, and decision-making methods will also emerge as complements to these new products and processes. To be successful in this competitive environment, industrial engineers will require significantly improved capabilities. The attainment of these capabilities represents one of the major challenges facing industrial engineers.

The 1998 publication *Visionary Manufacturing Challenges for 2020* [8] provides insights into the issues that will play a dominant role in the development of the competitive environment and technical scenarios anticipated in the future. It is important to note that the authors of this study originally defined *manufacturing* to mean the processes and entities that create and support products for customers. During the course of this study, however, it became increasingly clear that the definition of manufacturing will become even broader in the future as new configurations for the manufacturing enterprise emerge and the *distinctions between manufacturing and service industries become blurred.* This last message is particularly critical for the industrial engineer of the future, in which case the messages contained in this study shed considerable insight into the settings where industrial engineers will be working and the capabilities they should be acquiring or developing now to be viable and effective participants in this year 2020 scenario.

This study envisions manufacturing (and service) enterprises in 2020 bringing new ideas and innovations to the marketplace rapidly and effectively. Individuals and teams will learn new skills quickly because of advanced network-based learning, computer-based communication across extended enterprises, enhanced communications between people and machines, and improvements in the transaction and alliance infrastructure. Collaborative partnerships will be developed quickly by assembling the necessary resources from a highly distributed manufacturing (or service) capability in response to market opportunities and just as quickly dissolving them when the opportunities dissipate.

While manufacturing in 2020 will continue to be a human enterprise, it is envisioned that enterprise functions as we know them today (research and development, design engineering, manufacturing, marketing, and customer support) will be so highly integrated that they will function concurrently as virtually one entity that links customers to innovators of new products. New corporate architectures for enterprises will emerge, and although production resources will be distributed globally, fewer materials enterprises and a greater number of regional or community-based product enterprises will be connected to local markets. Extremely small-scale process building blocks that allow for synthesizing or forming new material forms and products may emerge as well. Nanofabrication processes will evolve from laboratory curiosities to production processes, and biotechnology will lead to the creation of new manufacturing processes with new and exciting applications on the shop floor of the twenty-first century.

Figure 1.1.3 summarizes both the "grand challenges" and key or priority technologies needed to address these challenges. While the terms used to define the grand challenges are familiar to most industrial engineers (concurrent manufacturing, integration of human and technical resources, conversion of information to knowledge, environmental compatibility,

Enabling Technology	Concurrent Manufacturing	Integration of Human & Technical Resources	Conversion of Information to Knowledge	Environmental Compatibility	Reconfigurable Enterprises	Innovative Processes
Adaptable and reconfigurable systems	✗	✗	✗		✗	✗
Waste-free processes				✗		✗
New materials processes				✗		✗
Biotechnology for manufacturing				✗		✗
Enterprise modeling & simulation	✗	✗	✗	✗	✗	✗
Information Technology	✗	✗	✗	✗	✗	✗
Improved design methodologies	✗			✗	✗	
Machine-human interface		✗	✗		✗	
Education & Training		✗	✗			
Collaboration software systems	✗				✗	

FIGURE 1.1.3 Applicability of priority technology areas to the grand challenges. (*From* Visionary Manufacturing Challenges for 2020 *[8]*.)

reconfigurable enterprises, and innovative processes), the challenge actually lies in achieving the level of capability envisioned as necessary to achieve the projected vision. For example, the goal of *concurrent manufacturing* is the ability to achieve concurrency *in all operations* of the supply chain—not just design and manufacturing. *Conversion of information to knowledge* is defined as the *instantaneous* transformation of information gathered from an array of diverse sources into knowledge useful for effective decision making. *Environmental compatibility* translates to *near zero* reduction of production waste and product environmental impact, while *innovative processes* refers to a focus on *decreasing dimensional scale.*

Finally, the key or priority technologies should be interpreted as the skill set that needs to be either enhanced or acquired to meet the grand challenges. While many industrial engineers are already significant players in a number of these areas (e.g., adaptable and reconfigurable systems, enterprise modeling and simulation, information technology, improved design methodologies, machine-human interfaces, and education and training), other areas such as waste-free processes, submicron and nanoscale manufacturing, biotechnology, and collaboration software systems represent opportunities for industrial engineers to expand their skill set in anticipation of future development. While the technology areas believed to have the most impact across the grand challenges (adaptable and reconfigurable systems, enterprise modeling and simulation, and information technology) are areas where many industrial engineers are currently involved, changes in the state of the art of these technologies is so rapid as to represent a continuous challenge for everyone in the profession.

SUMMARY AND CONCLUSIONS

The section titles of this handbook reflect much of the evolution and development of the industrial engineering profession and provide insights into its future and continuing challenges. The original motivation for the development of the field and the work of its early pioneers was driven by the desire to increase productivity through the analysis and design of organizational work methods and procedures and to provide a set of scientific principles that would serve as a foundation for continued studies of this nature. These efforts provided the framework upon which bodies of knowledge in the areas of work analysis and design, work measurement and standards, engineering economics, and production and facilities-planning functions emerged and established themselves as the underpinnings of the field. Concurrent efforts in behavioral aspects contributed to the knowledge base in compensation management and eventually led to the incorporation of issues associated with human performance, ergonomics, and safety as part of the scope of the profession. The arrival of operations research together with developments in computer technology provided the profession with a rich, new set of tools and technologies that significantly expanded the scope of the field beyond its original application areas and into areas such as information technologies and service applications. The need to reexamine the true impact of these innovations on organizational productivity has been a catalyst for more recent developments in areas such as product design and quality management, which have now become a major part of both the educational background and practice of today's industrial engineer.

Much of the attractiveness of industrial engineering lies in the fact that it is an engineering field that provides its members with a broad spectrum of career options. That the field has evolved in this way, from what could be considered rather narrow beginnings, has been primarily because of those in the profession who were not willing to accept boundaries and limitations regarding both the potential and promise of its principles, emerging technologies, and areas of application. Standing at the beginning of the twenty-first century, with slightly over 100 years of history under its belt, there is no reason to doubt that this dynamic field will continue to mature in its role as a global leader of societal change and provide its members with a wealth of new and challenging opportunities.

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BIOGRAPHY

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CHAPTER 1.2

THE ROLE AND CAREER OF THE INDUSTRIAL ENGINEER IN THE MODERN ORGANIZATION

Chris Billings
Walt Disney World Co.
Lake Buena Vista, Florida

Joseph J. Junguzza
Polaroid Corporation
Cambridge, Massachusetts

David F. Poirier
Hudson's Bay Company
Toronto, Ontario

Shahab Saeed
Mountain Fuel Supply Co.
Salt Lake City, Utah

The role and career of the industrial engineer in the modern organization can best be summed up the by word *diversity,* for there is hardly a profession, much less a discipline within engineering, that is so broadly defined. This chapter presents a series of case studies and examples of the diverse roles that industrial engineers play in several modern organizations and the many career paths available to them in organizations of this nature. The evolution of modern organizations and the resulting impact on the role of industrial engineers and the career paths open to them will be explored as well. Finally, the chapter will address the key success factors that have enabled many industrial engineers to advance their careers, as well as key threats to the discipline including *experts* that go by other names.

INTRODUCTION

In discussing the role and career of a field as broad and diverse as industrial engineering, it is important to gain perspective from a cross section of practitioners. This chapter has been coauthored by four individuals who are members of the Council on Industrial Engineering (CIE). The Council was formed by the Institute of Industrial Engineers (IIE) in 1963 and is comprised of top industrial engineers from a cross section of industries and countries. Its purpose is to provide a noncompetitive environment for sharing best practices and to discuss issues facing the industrial engineering profession. Some of the current companies represented on the Council include Boeing, General Motors, Deere, Philips, Kodak, and Kraft Foods.

In the authors' opinion, it is important to use true-life examples in portraying the role and career of industrial engineers. Therefore, a significant portion of this chapter will be anecdotal, relying on the authors' experiences within their respective companies and industries. The companies represented are Loblaw Companies; Hudson's Bay Company; Questar Corporation and its subsidiary, Mountain Fuel Supply Company; the Polaroid Corporation; and the Walt Disney World Company. While the examples are relevant to these and similar organizations, there are many roles and career paths that are not illustrated in this article and the focus here is largely on *organizational* as opposed to *technical* issues. Please note that the views expressed in this chapter are representative of the authors and not necessarily of the Council as a whole.

EVOLUTION OF THE MODERN ORGANIZATION

There is no doubt that the corporate environment and the competitive landscape have changed immensely in the last 10 years. The needs of organizations have grown more sophisticated and the business world has grown immensely more complex. The need to respond to trends that arise and change faster and faster, advanced technologies, the Internet economy, and greater expectations from customers have all put a phenomenal amount of pressure on traditional organizational structures and employee role definitions. "E-corporations" are emerging organizations that are not just using the Internet to alter their approach to markets and customers but are combining computers, the Web, and programs known as enterprise software to change everything about how they operate [1]. The resulting impact of these changes has made many traditional corporate organizational structures obsolete. Indeed, about the only constant in modern organizations is the presence of change at ever increasing speeds.

Organizations within North America have struggled to maintain and grow their competitiveness in the 1990s. With the movement toward the global and Internet economies, competitors are not found simply down the street or even in the next region, but in London, Tokyo, Seoul, and Beijing, and customers gain access to them with the click of a mouse. Forrester Research in Cambridge, Massachusetts, estimated Internet commerce at $50 billion in 1998 and that it will grow to $1.4 trillion by 2003 [2]. The individual has become the most powerful economic unit, which has given rise to mass customization. As one response to this reality, many corporations have tried to reengineer themselves. Modern organizations are seeking to organize themselves around their customers to increase speed and flexibility [3]. While the intent of reengineering was to reinvent processes by reducing unnecessary and non-value-added work to improve profitability and competitiveness, in many corporations it became the scapegoat blamed for downsizing and layoffs. As a result, many consultants and academics have begun to view reengineering as nothing more than a new paradigm for organizational and social change [4].

Shareholder expectations for higher investment returns have helped fuel a drive for greater efficiency and have placed increased pressure on companies to raise the expectations of their employees. The "leaner and meaner" attitude coupled with the last cycle of corporate downsizing has brought about a change in the fundamental relationship between employer and employee. With lifetime employment a thing of the past, many employees feel the pressure to add value every day to simply hold on to their current jobs, much less to advance their careers. On the other hand, economic growth has created thousands of new jobs making employees in many organizations more likely than ever to leave for a better opportunity. In addition, "de-layering" has pushed decision making to lower and lower levels within organizations through the reduction of many middle manager positions.

Organizations have had to evolve their thinking, expectations, and structures in response to all of these fundamental changes in the business environment. In turn, organizations have altered their expectations of what employees need to deliver. These factors are a few of the reasons why the role and career of the industrial engineer have evolved so significantly over the last 20 years.

THE INDUSTRIAL ENGINEER'S ROLE

Industrial engineers many times encounter people who do not understand or are unfamiliar with the term *industrial engineer.* Indeed, probably the most commonly asked question of an industrial engineer in the workplace or outside may be, "What do industrial engineers really do?" IIE defines industrial engineering as being "concerned with the design, improvement, and installation of integrated systems of people, materials, information, equipment, and energy. It draws upon specialized knowledge and skill in the mathematical, physical, and social sciences, together with the principles and methods of engineering analysis and design to specify, predict, and evaluate the results to be obtained from such systems." This definition certainly does not succinctly describe what industrial engineers do.

One of the great challenges of the IE profession is communicating the distinct roles that industrial engineers play when the roles are so diverse and varied across organizations. From a historical viewpoint, and to some extent still today, industrial engineers are perceived to be stopwatch-and-clipboard-bound supervisors. A hope for the future is that they will come to be known and respected in more enlightened organizations for their roles as troubleshooters, productivity improvement experts, systems analysts, new project managers, continuous process improvement engineers, plant managers, vice presidents of operations, and CEOs. While confusion over the roles of industrial engineers can be a liability, it also presents opportunities that arise when expectations are allowed to evolve. In many organizations the roles of industrial engineers have become highly evolved and many industrial engineering departments have grown to fill a unique niche. Still, the term *industrial engineer* largely says more about the training and degree, and less about the actual role played in most organizations.

The industrial engineering education is an excellent foundation for careers of choice in today's business environment. It is comprised of a multitude of different skills and tools that enable the industrial engineer to act as a master of change and thus make a tremendous impact in any type of organization. The industrial engineer's ability to understand how activities contribute to cost and/or revenue give him or her an advantage in leading divisional or enterprisewide process improvement initiatives. The fact that industrial engineers will spend time to study and thoroughly understand the current activities of an organization and will be able to link changes to improvement in financial terms, makes the industrial engineer a valuable asset to the organization. Understanding the current activities, applying creative solutions to current problems, and measuring their impact in the context of strategy are some of the best contributions an industrial engineer can make. The ability of many industrial engineers to relate to coworkers in different departments such as information systems, operations, and finance makes them great assets in many large organizations.

The ability to understand the constraints and needs of different areas of the business and translate it to other participants in a change initiative is also something that not all professionals have. Industrial engineers with this ability are good candidates to facilitate different forces in an organization, a role that can make the difference between a successful change initiative and one that fails. In addition, the ability to learn the activities of an organization on a detailed level, coupled with a knowledge of finance and budgeting, helps to groom the industrial engineer to become the decision maker of tomorrow. These are some of the reasons a number of industrial engineers are reaching high levels in today's organizations.

A survey of one dozen companies represented on the CIE reveals the diversity found among the roles that industrial engineers play in various companies (see Table 1.2.1). While there are some significant differences, these five general roles are predominate: process improvement expert, systems integrator, change agent, productivity expert, and model developer.

In addition to these roles, many industrial engineers play the role of facilitator/team leader on many change initiatives. In today's increasingly complex modern organizations, most tasks are accomplished by individuals partnering and working together. Formal partnering usually involves multidisciplinary teamwork. In many cases, industrial engineers have the broad background and experience to serve as effective facilitators because they are perceived as objective and balanced in their approach.

Canadian Retailing

Loblaw Companies is the largest retail and wholesale food distributor in Canada with $18 billion (Canadian dollars) in 1999 sales. At Loblaw, industrial engineers have had the opportunity to grow in many ways. There are industrial engineers in almost every division of the business: in operations (retail, distribution, transport), at head office (finance, administration, information systems, procurement), and as change agents, project managers, and internal consultants. Industrial engineers are also present at the executive level of the organization.

Industrial engineers have been present in the Loblaw organization for almost 20 years. At first, they were spread around the business to support the core distribution activities, and then they moved to a separate head office division, acting as internal consultants for most change initiatives happening in the business. The industrial engineering department has since established itself in the business units. Divisions now recognize the value that an industrial engineer brings to a change initiative and most now require that one be assigned before starting the initiative. The department has become involved in every aspect of the business: manufacturing, transport, distribution, logistics, retail, information system design, information flow design, procurement, supply chain management, performance measurement, and more. The department was initially involved in methods engineering and labor measurement initiatives.

Hudson's Bay Company is North America's oldest retailer. Founded in 1670, the company has grown to be the largest retailer of general merchandise in Canada. The challenge of keeping an organization successful as it enters its fourth century of operation rests on the organization's ability to transform itself from what made it successful in the past to what it must be to meet the new expectations of consumers. The introduction of building industrial engineering competency began in 1998. Since that time, the function of industrial engineering has brought process improvement to the fulfillment of the shopping experience at Hudson's Bay Company stores throughout Canada.

Today, these retail organizations are relying on industrial engineers to bring these tools and techniques to the business to contain operational costs. However, the companies realize that the knowledge built in applying these skills can be used in other types of change initiatives. By building its expertise in understanding how a subsystem can contribute to the improvement of the overall system, the department has built a unique understanding of the big picture. The industrial engineers are now involved in new types of initiatives from implementing new technologies to solving logistical network problems and systems design. The activities range from operational problem solving to strategic initiatives. The following are examples of a few projects where industrial engineers are a key asset:

- *Warehouse management system design and implementation.* The industrial engineers gained experience implementing an off-the-shelf warehouse management system package. This allowed them to play an important role in designing a leading edge real-time system that includes capabilities far beyond what has been seen in such systems today. The industrial

TABLE 1.2.1 Roles of Industrial Engineers

	IE roles							
Company	Process improvement expert	Systems integrator	New product developer	Change agent	Capacity planner	Demand forecaster	Productivity expert	Model developer
Boeing	X	X	X	X	X	X	X	X
Canadian Imperial Bank	X	X	X	X	X		X	X
COATS North America	X	X		X			X	X
Coors Brewing	X	X		X	X		X	X
Dover Resources	X	X		X	X		X	
Kraft Foods	X	X		X			X	X
Questar Regulated Services	X	X		X			X	X
Made 2 Manage Systems	X	X	X	X				
Norfolk Southern	X			X	X		X	X
Raytheon Systems	X	X		X	X	X	X	
Textron	X	X		X	X			X
Walt Disney World	X	X		X	X	X	X	X

Source: Survey of Council on Industrial Engineering membership—1998.

engineers also contributed to many other aspects of this project, including developing requirements and translating them into understandable terminology, defining systems capability and user interface requirements, project managing tight timelines, facilitating business decisions, training the users, and more.

- *Distribution network design.* The retail business has been drastically transforming its distribution network to improve service levels and product quality, to optimize asset utilization, and to face the ever-increasing requirements of customers while reducing inventory levels. Industrial engineers have been instrumental in leading the analysis of the network and modeling future alternatives. Again their knowledge of operations was critical. Coupling business knowledge and simulation technology, the team was able to become a critical link in the success of this endeavor. As a result of this modeling initiative, the business is entering into its biggest transformation to date.
- *Labor management system design and implementation.* Industrial engineers have been involved with deploying a labor management system at the retail level. This was possible because of the knowledge of methods engineering, labor standards, and system design. A lot of the expertise was gained through involvement in process improvement initiatives achieved throughout distribution operations. Industrial engineers studied the operation, developed best practices, designed system specifications, interfaced with operations personnel, and managed the implementation. In addition, they created and implemented measurement systems that were critical to realizing the expected benefits.
- *Store design and process improvement.* In this initiative, industrial engineers focused on methods and process improvement to enhance the customer experience in stores and improve the efficiency and effectiveness of the labor deployed in the retail environment.

These are only a few examples of the projects in which industrial engineers are involved at Canadian retail companies. Their work has resulted in substantial financial benefits, which are expected to increase in the future as the learning curve matures.

Walt Disney World

Walt Disney World Resort holds the titles of “The World’s Number One Vacation Destination” and “the largest single-site employer in the United States.” The resort consists of 4 theme parks, 3 water parks, 16 resort hotels, 2 nighttime entertainment centers, over 80 attractions, over 250 restaurants and retail shops, 5 golf courses, 2 cruise ships, and 1 sports complex. These operating businesses are spread among 30,000 acres of land and together create an environment that is a “dream world” for industrial engineers relative to all of the application opportunities that exist.

Industrial engineering at Walt Disney World dates back to the beginning of the company in 1971. Industrial engineers at this time supported the facilities maintenance and central shops (the manufacturing arm of the company) functions, largely facilitating methods improvement, downtime analysis, and job shop planning and scheduling. The industrial engineering organization formally came into existence in the late 1970s and was most recently centralized into its current corporate role in 1988. The role of the IE has evolved tremendously since its inception and today the department supports nearly every part of this expansive business. The following are examples of a few projects in which industrial engineers have played, and continue to play, a key role at Walt Disney World.

Productivity Improvement. With over 55,000 cast members (i.e., employees), labor represents the largest controllable cost at Walt Disney World. Productivity initiatives have become increasingly important in leveraging economies of scale and controlling labor costs. Industrial engineers are involved with initiatives across all lines of business and business units and play a critical role in leading many of these efforts.

Guest Flow Analysis. Industrial engineers play an integral part in understanding and modeling guest behavior in the theme park environment. This analysis affects decisions to add or reduce operating capacity, the implementation of new ways to improve the guest experience, and various productivity analyses. Guest flow analysis is performed throughout the theme parks, resorts, and transportation system operations.

Capacity Sizing. The Industrial engineering team is responsible for developing the capacity programs for new theme park ventures as well as for additions to the existing parks. These efforts entail modeling and projecting guest demand so that the optimal amount of capacity needed to provide adequate attraction, food and beverage, retail, and support service capacity can be derived.

Labor Forecasting and Scheduling. The industrial engineering organization was responsible for the development and management of the labor scheduling system used to produce weekly schedules for over 25,000 cast members who work the frontline operations spread throughout the resort complex. This effort involved revamping the key processes for how labor was scheduled, specifying the needs of the system, the justification and implementation of it, and the training and ongoing maintenance for it.

Key Success Factors

While the role of industrial engineers can and does vary widely across modern organizations, certain factors are evident in those organizations in which industrial engineers have enjoyed much success. The following are several key success factors for ensuring the effectiveness of the industrial engineer's role.

Be Flexible, but Focused. Today's industrial engineer should be open to new assignments and look for opportunities to contribute in new ways. Expectations of industrial engineers change as the organization changes and the most successful ones respond by evolving their role to stay in sync with the overall organization. At the same time, in whatever role industrial engineers play, they should strive to maintain a focus on value-added work. Surveys of U.S. industries show that employees spend only 25 percent of their time on average doing value-added tasks [5].

Apply Industrial Engineering Concepts to Real-World Problems. To understand a theory is only part of the challenge; understanding how to use it in a real-life problem is the true challenge. Too often, younger engineers apply "recipes" without understanding their limitations, thus relying on flawed assumptions to justify new projects. The true understanding of how concepts are applicable makes a very important difference in the long-term success of projects or change initiatives. Another challenge is being able to explain to higher management how these theoretical concepts translate into bottom-line value for the organization. Most of the concepts taught in school rely on solid data; if not researched properly, incorrect data will invalidate expensive analysis (e.g., simulation modeling). Complex models can be built, but they will not mean anything if valid data is not used.

Understand the "Big Picture"—How Change Initiatives Impact the Overall Organization. System thinking is a skill that every industrial engineer should possess. Understanding how a change can impact an organization is essential in truly having a positive impact on the bottom line. It is easy to perform a process improvement on a subsystem, but understanding and conveying how it benefits the whole organization is what's really important.

Understand and Analyze the Current Processes Accurately. To understand current processes an industrial engineer must live the day-to-day reality of the shop floor. Only a true comprehension of current reality will enable the best process improvement alternative: Not understanding presents the risk of pushing solutions that look great on paper, but don't answer the fundamental need of an operation. Often, simple changes yield large returns and allow for the discovery of the true long-term process improvement alternatives. It is also important to properly apply basic knowledge and techniques on a problem before implementing complex solutions. Failing to do so can generate problems for the sustainability of a solution.

Manage Change. People manage all processes. If the people affected by the changes are not convinced of the solution, there are many ways in which they can contribute to its failure. Helping key players understand the importance of the change and the benefits it will bring to the organization is a challenging but important task. Most failures in projects can be attributed to a poor change management process. Figuring out a new solution on paper is easier than predicting human reaction to the changes. Ask, "What does it mean for the people affected?" Not taking the time to understand what is at stake will likely result in project failure in the long run.

Follow Through on Implementation. Too often the mistake is made of assuming that if a project is implemented successfully, the benefits will be recovered. This is a mistake to avoid at all costs. The goal of an industrial engineer is to create value. Overlooking the securing of savings that are generated by a successful project is like forgetting to take home the groceries you paid for at the store. It is up to the industrial engineer to ensure that a measurement or tracking system is put into place, following a project implementation. Benefits as well as project costs should be tracked to the bottom line.

Be Creative. The ability to see current reality and generate new ideas is what brings the most value to any changing organization. The industrial engineering education provides useful skills and techniques that can be applied to any process, from manufacturing to the service industry. The industrial engineering profession is continuously growing in new areas because of the people who used their creativity to apply their knowledge outside of the traditional field of industrial engineering practice. The success of industrial engineers in nontraditional areas, such as logistics, health care, theme parks, banking, and retail, can be attributed to visionaries who could see the potential and convince decision makers to invest time and energy in these new change initiatives. By being creative, an industrial engineer can generate substantially more value to an organization than would be initially expected.

Communicate Clearly. To put ideas into practice, an industrial engineer must also possess excellent verbal and written communication skills. Most of the process improvements recommended by industrial engineers involve techniques or technologies that can be complex. These solutions could have a sizable impact on the business but may require significant investments. The ability to present recommendations to decision makers in a way that they can readily comprehend requires that industrial engineers work on creating clarity.

Decision making has to be based on understandable facts that are supported scientifically. Reporting results and financial information in an understandable way is also critical in gaining and maintaining the trust level of senior management. Complex projects may take years to complete and ongoing communication of milestones is critical in ensuring continuous support for current and future projects.

Many industrial engineers' education and experience position them well to make significant contributions to organizational performance improvement across most industries and sectors. Their unique combination of skills and thinking practices affords them opportunities to have a meaningful impact on how organizations operate and remain competitive. It is a rewarding role for both the individual and the organization.

Key Threats

A number of potential threats to the success of the industrial engineer exist that can come from within or without the organization. Avoiding the following pitfalls can go a long way toward protecting and growing the value of the industrial engineer's role.

Lack of Appreciation for the Discipline. Industrial engineering is a discipline that needs to be continually sold. Industrial engineers have been grappling with the profession's image for the last 50 years as evidenced by letters to the editor in the first issue of the *Journal of Industrial Engineering* in June 1949 about the necessity of selling industrial engineering [6]. Within their organizations, industrial engineers need to establish a reputation for recruiting and developing top talent. The success of the industrial engineering discipline will be greatly enhanced if this talent is able to develop and migrate into key leadership positions. Leaders who share an industrial engineering legacy will help fuel the demand for industrial engineering support and institutionalize a respect for the discipline.

Failure to Align with Key Business Challenges. This is the antithesis of being flexible. If the industrial engineer's role within an organization does not adapt with the company and continue to serve the greatest need, it most likely will not thrive, and potentially, may not survive. Whether the business strategy involves growth or cost containment, industrial engineers need to position themselves to contribute the greatest value.

Failure to Evolve. Perhaps there would not exist such a proliferation of management consultants and process improvement experts (that go by names other than industrial engineer) had industrial engineers in many organizations and the profession at large been more adept at recognizing opportunities. Demand for this expertise surfaced abruptly, grew tremendously, and overwhelmed most industrial engineering organizations. It was a strategic opportunity that the profession may have missed. While it has been, and still is, a significant challenge to market the profession, industrial engineers have the responsibility of marketing themselves. Those who do a good job of this are likely to reap the benefits of new opportunities that appear on the landscape before other so-called experts are called in.

CAREER PATHS OF INDUSTRIAL ENGINEERS

Diversity is the word that best sums up the career paths available to industrial engineers. The broad training, experience, and exposure that industrial engineers receive enable many to advance their careers to very high levels within their organizations. This section will attempt to convey via real examples the true breadth and diversity of the career paths that industrial engineers can follow. These career path anecdotes comprise a sample cross section of industries, company sizes, and geographic locations. Table 1.2.2 indicates some of the career paths open to industrial engineers within select organizations that took part in the CIE survey.

Canadian Retailing

The industrial engineering departments at major Canadian retailers provide excellent opportunities for career growth. Industrial engineers can choose among many career options. Some industrial engineers will become specialists that provide a unique service to the companies, in such areas as simulation, measurement, systems design, and process improvement. Others will choose a management career. The first project engineer for Loblaw Companies went on to become senior vice president of the organization. The executive vice president of Hudson's Bay Company is an industrial engineer. He is now involved in long-term planning for the

TABLE 1.2.2 Example Career Paths of Industrial Engineers

Company	Career paths					
	Position 1	Position 2	Position 3	Position 4	Position 5	Position 6
Boeing	Industrial engineer/ analyst	Industrial analyst	Manager	Senior manager		
Canadian Imperial Bank	Junior analyst	Intermediate analyst	Senior analyst	Consultant/ project manager	Senior consultant/ project director	Vice president
Kraft Foods	Manufacturing engineer	Area staff manager	Business team manufacturing engineer	Area manufacturing engineering manager		
	Manufacturing engineer	Plant supervisor	Production department head	Plant manager	Director, operations	
Raytheon Systems	Manufacturing engineer	Lab engineer	Agility manager	Director of quality		
	Facilities engineer	Facilities manager	Coporate real estate manager	Director of facilities		
Walt Disney World	Associate IE	IE	Senior IE	Manager, IE	Director, IE	
	IE	Senior IE	Manager, facilities maintenance	General manager, maintenance services	Vice president, maintenance	
	Senior IE	Manager, IE	Director, IE	General manager, operations	General manager, operations	Vice president, operations

Source: Survey of Council on Industrial Engineering membership—1998.

organization. Still others will choose to continue their career in other divisions. Industrial engineers are now found at executive levels in distribution, operations, and logistics throughout Canadian retailing.

Walt Disney World

The first few industrial engineers at Walt Disney World supported the facilities maintenance side of the business. One entrepreneurial industrial engineer saw the potential to apply industrial engineering to do so much more and started to branch out and demonstrate the value of the profession to other parts of the company. As the company grew, so did this individual's career; he soon found himself promoted to industrial engineering manager. As the industrial engineering function expanded it became fragmented and was "owned" by the areas it supported. This individual left industrial engineering in the early 1980s and took on roles of increasing responsibility such as director of design and engineering, general manager of operations, vice president of operations, and his current position as executive vice president, operations planning and development.

Another example of an industrial engineering career path is that of a woman who began her career at the same company in the mid-1980s. After working her way up the career ladder from industrial engineer to senior industrial engineer to manager, she was promoted to director when the industrial engineering department was centralized. She subsequently went on to two general management positions with theme parks and resorts operations. She is currently a vice president with responsibility for running half of the Walt Disney World resort hotels.

A third example is the current director of transportation planning who is responsible for guest transportation infrastructure planning and implementation. His career with the industrial engineering organization spanned some 16 years beginning as an undergraduate co-op student. After a brief stint with another company, he returned as a full-time industrial engineer in 1985. He progressed through many diverse assignments and positions (such as a year and a half in Europe as the manager of operational planning for Euro Disney) that ultimately led to the director of industrial engineering position. This individual never thought he would remain an industrial engineer for more than five years, but the challenging opportunities that were available always kept him fulfilled and allowed for his continued growth and development.

Since the early 1970s, the industrial engineering team at Walt Disney World has grown from a handful to well over 60. Industrial engineers from this organization have moved into a multitude of roles befitting the diverse nature of Walt Disney World. The industrial engineering skill set is common in people who hold these job titles: manager of transportation operations, vice president of resort operations, general manager of water parks and recreation, vice president of market research, vice president of attractions planning, productivity manager, and director of labor strategy.

Questar

Diverse is also the best way to sum up the careers of two industrial engineers working for Questar Corporation, a diversified energy company with assets of nearly $2 billion. Both individuals actually worked in the industrial engineering department and served as director of industrial engineering.

The first example features a gentleman who is now a vice president and general manager of Questar Pipeline Company. He received a degree in industrial engineering with honors from the University of Utah in 1979. He is a registered professional industrial engineer in Utah and Wyoming and has held many positions with the Questar Corporation including vice president, regulatory affairs, Questar Pipeline Company; vice president, regulatory affairs, Mountain Fuel Supply Company; and vice president, marketing, Mountain Fuel Supply Company. His current position involves the management responsibility for $410 million in identifiable assets for Questar Pipeline Company, which generates about $105 million in revenues and about $27 million in net income for its parent, Questar Corporation. He is responsible for the operation and maintenance of over 1,500 miles of pipeline, four major natural gas storage facilities, and the construction of new pipeline and related facilities. He manages an annual operation budget of about $25 million and a capital budget of about $40 million. His position also includes responsibilities for Questar Pipeline's customer service, as well as managing the relationships between Questar Pipeline and Questar Regulated Services Company, which provides administration, engineering, marketing, and other services to Questar Pipeline.

The interesting fact about this industrial engineer's career is that he started as a utility man, installing gas pipelines. When he was in his mid-30s, he resumed his formal engineering education and had the opportunity to be involved in higher level management at the Questar Corporation at the same time he was pursuing his degree. It became clear to him that sound technical management was required in nearly every position at a company like Questar. Furthermore, he discovered that a company comprises many interlinked business processes and that the key to increased productivity was to understand the role each of these functions has with the others. Industrial engineering offered the technical regimen, such as the study of fluid flow, structures, engineering economics, engineering statistics, and operations research, to understand the interlinked processes. It also provided an opportunity to take courses in marketing, industrial psychology, finance, and other disciplines that were extremely useful in dealing with executives in charge of these activities. The industrial engineering field of study was the best preparation this individual could have had for a diversified career in a major corporation.

Another example at Questar is an individual who is currently the director of marketing for Questar Regulated Services, which includes both Mountain Fuel Supply and Questar Pipeline, Questar's interstate natural gas pipeline. The worth of these pipeline systems is approximately $1.5 billion. He is responsible for marketing pipeline transportation service to end-use customers, gas marketers, and gas producers throughout the western United States. He also served as director of industrial engineering—only in this case his academic career began very differently. His early studies at the University of Utah were in chemistry. After one year, he made the transition to chemical engineering. As he was taking the required basic engineering courses, he literally stumbled into an engineering economics class taught in the industrial engineering department and found that he enjoyed the course and the professors who taught there. It was the perfect mix of engineering and business.

After receiving his B.S.I.E. (bachelor of science in industrial engineering) at the University of Utah, he was convinced by his major professor to attend Virginia Tech. There he received an M.S. in operations research and industrial engineering and started work on a Ph.D. at the University of Arizona in systems engineering. At the time he was going to school at Arizona, the employment opportunities were much better for engineers with a master's degree than those with a doctorate, so he decided to enter the job market. He found a position in Salt Lake City with Mountain Fuel Supply Company (the local natural gas utility and Questar subsidiary) and began work in the newly created industrial engineering department. After two years he was made a supervisor in the department and a year later the department director. The primary focus of the department became productivity improvement. At a national IIE (then AIIE) conference he became aware of the new concept of quality circles. Quality circles were a perfect fit for Mountain Fuel's productivity needs, and it became the first gas utility in the United States to implement quality circles.

Based on his work with operating people in quality circles and his technical expertise, the vice president of operations asked him to become the manager of operations for the Salt Lake City division of Mountain Fuel. The knowledge provided by his industrial engineering background concerning productivity, systems, manpower requirements, budgeting, and organizational development all came to the forefront in this position. After five years he was asked to head the industrial marketing effort for Mountain Fuel, focusing on the company's largest customers. An understanding of industrial processes and the ability to interface with all types of people from the boiler operator to the president of the company were required. The other industrial engineering skill set that was needed was in the area of engineering economics. He learned that when competing for a customer's business it is essential to have the knowledge and tools available to develop economic scenarios that demonstrate why his company's product should be used instead of the competition's. He also supplemented his industrial engineering education with marketing and sales classes to learn how best to meet his customers' needs.

Polaroid

Polaroid, the well-known manufacturer of imaging products, is another organization where industrial engineers have followed a variety of career paths. One such IE career path has spanned some 37 years and can be described as "simple in its beginning and extremely diverse in its pathways." This individual is currently involved in the start-up of a new business that is aided by his diverse business experiences. He sums up his career philosophy in the statement: "Diversity of tools leads to diversity of opportunities yields diversity of experiences, learnings, and fulfillment."

This industrial engineer graduated from Northeastern University in Boston, Massachusetts, with a B.S.I.E. in 1961 and an MS in engineering management in 1968. He began his career in 1961 with the Foxboro Company as a methods engineer. From 1962 to 1978 he worked at the headquarters of GTE Sylvania as a stopwatch time-study engineer. His job entailed traveling to 22 factories to set labor performance standards, create wage payment plans, and conduct studies to solve operational problems. This experience quickly seasoned him to the rigor of getting tasks done in allotted time frames. The exposure to local, divisional, and corporate management plus his job performance yielded requests for resolving special problems, such as establishing a feeder factory in the Mexican border zone, outfitting machinery at a factory in Costa Rica, laying out the corporate president's apartment in Manhattan, and almost landing a quality assurance manager's job in Naples, Italy. Other positions he held at Sylvania headquarters included group leader/supervisor, manager of auditing and training, and division manager of cost controls.

He credits the tools, skills, and attributes of the industrial engineering trade with teaching him how to approach any situation by simultaneously considering the whole, as well as the key parts. Fundamental questions from "Why does this even exist?" to "How does this piece work?" frequently permitted a clear and easy focus on what had to be done. There were no constraints or tool limitations to the initial scoping of a task or problem. It was then not difficult to also define what additional specialized skills were needed to successfully complete the task and how to manage success.

This engineer's next assignment took him to Sylvania's Kentucky factory where he became the manager of product design and engineering and support functions. The transition from "headquarters contributor" to line responsibility was easy, planned, and fun. In this role, he called upon all of the past industrial engineering tools and "approaches to defining and solving the problem" that he had learned. From there he became a division manager and had responsibility for special projects reporting to the president of the Wilber B. Driver Company in Newark, New Jersey. He has worked for Polaroid since 1978 and has held the positions of chief industrial engineer, camera factory; senior engineer, central industrial engineering; internal consultant; and most recently as senior manager, sales and marketing.

The next example career path from Polaroid is that of an individual who became interested in industrial engineering when he was a student at Northeastern University. His first co-op job while in college was to collect and analyze time study data at an RCA Defense Electronics plant where components were being made for the Apollo Lunar Module. His next co-op job was with Polaroid, where he has been employed since 1971. He was first assigned to the film assembly division, where he learned a great deal about high-volume automated manufacturing and packaging operations. At that time, Polaroid had a centralized industrial engineering department; engineers were deployed at strategic locations with responsibility for cost reductions and operational improvements. His co-op experience and industrial engineering education enabled him to progress through a series of positions at Polaroid with increasing levels of responsibility. Along the way he was able to obtain a master's degree in manufacturing engineering, and his thesis subject was the resolution to a real-world shipping and logistics problem between the domestic and international manufacturing divisions. He has held positions as a technical supervisor, quality control supervisor, plant engineer, technical manager, and engineering manager. His project experience has included the design and implementation of integrated materials handling systems, a major upgrade of a central utility plant, administration of an energy conservation program, and installation of facilities and equipment to increase plant capacity for continuous flow manufacturing processes.

Outside his career opportunities, this individual has also found his industrial engineering background to be of value when applied to everyday events. For example, he became involved in a local effort to raise money and build a handicapped accessible playground in his community. When he joined the committee they had been in existence for over two years, had no organized plan, no construction schedule, and no concept of how to actually get the playground built. He ended up teaching them about program evaluation and review technique (PERT) charts, equipment layouts, and vendor selection criteria. Six months later the playground was complete, and a whole new audience had an appreciation for industrial engineering at work and at play.

The final Polaroid example is an individual who graduated with a B.S.I.E. from Newark College of Engineering in 1964. In the 34 years since then, his industrial engineering background has served him exceedingly well, and in some cases, quite unexpectedly. He began his professional life as a safety engineer in a railcar manufacturing facility. Why would anyone assign an industrial engineer to be a safety engineer? The reason was simple: The company was losing a fortune in compensation payments and they wanted someone to figure out what to do about it. An early lesson was learned—industrial engineers went where the problems were, and the problems usually had to do with financial loss. From there he went to work for Johnson & Johnson (J&J) as an industrial engineer and stayed there for almost 14 years. Initially he worked in distribution and was able to apply many of the traditional IE skills including work measurement, workplace layout, linear programming, and make versus buy decisions. But the most significant thing this exposure provided was an early opportunity to work as a first-line supervisor—dealing with the distribution operations and the people who made them run. He learned to deal with supervisory issues at an early age, and the lessons learned have served him well.

The remainder of this industrial engineer's career at J&J was spent moving back and forth between line and staff assignments, in both distribution and manufacturing. Jobs he held included manufacturing operations manager for an extrusion coating department where his industrial engineering background helped him learn and succeed in "making the numbers," which is a fundamental tenet of any line assignment. He moved on to manage several industrial engineering departments within the site, and at the end of his J&J career was functioning as the chief industrial engineer of the eastern facilities. As he reflects on those days, he realizes that the strength of the industrial engineering discipline was as an integrator of facts and opinions for the good of the enterprise. This allowed him to move into assignments in both line and staff that capitalized on this integrative skill set, providing a certain freedom of choice not necessarily available to other engineering disciplines.

In 1979, he moved from J&J to Polaroid where his initial assignment was to manage a central industrial engineering group. This group provided support to the entire company with the exception of the major manufacturing facilities; they had their own industrial engineering departments that supported some traditional disciplines such as purchasing, finance, and marketing and sales. Next he was promoted to manage the industrial engineering function worldwide, and did so for approximately five years. From there he moved on to head a team tasked with the development and implementation of a new product delivery process. The primary reason he was selected for this job was the breadth of experience developed as an industrial engineer. He has engaged with just about every segment of the company in his initial nine years, and he led the development and installation of the Polaroid Product Development Process that is still used today.

From there he was asked to join corporate strategic planning. His assignments ranged from an analysis of how to defend the company from hostile takeovers to what actions were needed to reduce working capital. Again, his varied background made him a good candidate since so many pieces of the corporation came into play. He spent the next three years on the design team charged with creating a total quality management (TQM) strategy for the company. This experience enabled him to be selected as Polaroid's representative in a consortium of Cambridge-based companies whose goal was to establish a TQM-based institution for the learning and improvement of all member companies, which evolved into the Center for Quality Management. Now this industrial engineer has returned to his most rewarding and fulfilling work: program management. On and off over the last 10 years he's had the privilege of leading a new product program team with responsibility for taking an idea, turning it into a product concept with the help of the marketplace, and then designing, developing, manufacturing, launching, and marketing the new products worldwide. It is the best job he's ever had, one that employs all the skills and experiences his industrial engineering days provided.

Key Success Factors

Several attributes make industrial engineers candidates of choice for diverse job opportunities in many businesses. The experience gained through project work on the shop floor gives the industrial engineer a good understanding of the operation. Their understanding of economic analysis and the link with operational activities make them effective decision makers. Communication skills are also critical in being able to communicate with frontline employees or senior management.

Besides their educational backgrounds, what most all of the successful industrial engineers mentioned here have in common is that many became leaders of key projects and initiatives that were highly visible and successful. In large organizations, it can be difficult to be noticed. Fortunately, for many of them, their skill set was portable and was enabled by the varied scope of their role that allowed them to gain exposure across the organization. The rest was largely up to them. The following are some key success factors cited as having helped advance their careers.

- Collect experiences—be willing to take on challenging new work and be open to new assignments.
- Continue your education—learning should be a lifetime commitment.
- Maintain a positive attitude—everyone wants these types of people on their team.
- Fill a gap—don't limit your thinking and contribution to your job description or to roles that exist on an organizational chart (stay abreast of key challenges facing your company or organization, recognize an opportunity, and create your own role by filling unmet critical needs).
- Learn to be a generalist and think strategically—use the experiences you collect to "round" yourself out and fill in the big picture.
- Develop and maintain a reputation for getting things done—become known for driving projects to completion and for a strong list of accomplishments.
- Communicate effectively—be effective at communicating with all types of people and personalities from frontline employees to senior management.
- Learn to negotiate—few things in life are accomplished without some give and take.

- Network well and often—key clients today can become mentors tomorrow; key contacts today can become links to opening new career doors tomorrow.

In addition to these success factors, industrial engineers beginning their careers should recognize that career development is primarily the responsibility of the individual. If an individual is lucky enough to be working for an organization that takes career development seriously and has a formal process, he or she should take full advantage of it. One should never assume that it is someone else's job to look after his or her career interests. Industrial engineers should focus on excelling at the job they have today, and the opportunities will most likely be there in the future. Some engineers get caught up in thinking too much about their next project, assignment, or position and do less than their best work. This path rarely leads to career growth.

CONCLUSIONS

Successful industrial engineers' roles are increasingly diverse and they, as well as the profession, must continue to evolve to remain relevant. The industrial engineering skill set is well suited for the fast paced, changing environment of modern organizations.

It is nearly impossible to convey the full breadth and diversity of the roles and career paths that industrial engineers are experiencing in one chapter. One thing all of them have in common, however, is the need to stay current with the latest trends impacting their organizations. A critical challenge facing organizations entering this millennium is the increasing pace of change in improving the organization. This challenge requires people who can understand new concepts and technologies and their impact on operations and people. Industrial engineers of today and the future need to position themselves to meet these challenges and leverage this opportunity. Those who do so will enjoy rewarding roles, as well as successful careers.

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BIOGRAPHIES

Chris Billings is the director of transportation planning for the Walt Disney World Company based in Lake Buena Vista, Florida. Prior to his current role, he was most recently the director of industrial engineering. Chris's career at Disney spans over 16 years and has comprised numerous positions within the industrial engineering organization, involving many key business planning and process improvement initiatives. He earned a bachelor's degree in industrial engineering from Georgia Tech and a master's in business administration from the Crummer Graduate School of Business at Rollins College. He is a senior member of the Institute of Industrial Engineers (IIE), a member of the Council on Industrial Engineering (CIE), and a member of IIE's Education Policy Advisory Board to the Accreditation Board for Engineering and Technology (ABET).

Joseph J. Junguzza is currently a director of product development for the Polaroid Corporation, focusing on the next generation of imaging technologies and products. Joe has been with Polaroid for 20 years. His prior responsibilities include worldwide director of industrial engineering, director of total quality management, director of the product development process, and program director for numerous imaging hardware and media products. Prior to joining Polaroid, Joe spent 14 years at Johnson & Johnson with positions in manufacturing, distribution, and engineering. He received his degree in industrial engineering from Newark College of Engineering (New Jersey Institute of Technology). He has served on the Council on Industrial Engineering for over 15 years.

David Poirier, P.Eng., P.Log., is currently executive vice president of Hudson's Bay Company (HBC) in Toronto, Canada. Prior to joining HBC, Dave spent 17 years with Loblaw Companies where he held various positions in distribution, procurement, corporate development, and information systems. Dave received his degree in industrial engineering from the University of Toronto and has also earned the designation as a professional logistician from the Canadian Professional Logistics Institute. He is a past IIE board member, member of the Council of Industrial Engineers, and past recipient of the Outstanding Young Industrial Engineer Award. Dave's participation in other professional associations includes chairman of the Logistics Institute in Canada and member of the board of governors for the Uniform Code Council. Dave is also an adjunct professor at the University of Toronto for the faculty of applied science and engineering.

Shahab Saeed, P.E., is the director of administrative services for Questar Regulated Services, an energy company with 1998 revenues of over $580 million. As a member of the management committee, he directs the activities of administrative functions including continuous improvement, human resources, facilities, safety, environmental, security, communication systems, fleet, purchasing, and materials management services for the company and its two wholly owned subsidiaries: Questar Pipeline and Questar Gas. Shahab received a degree in industrial engineering with honors and an M.B.A. from the University of Utah. The Institute of Industrial Engineers selected him as the 1994 Outstanding Young Industrial Engineer. He is a faculty member at Westminster College, Gore School of Business in Salt Lake City, as well as the Landegg Academy's School of Leadership and Management in Switzerland. Shahab is also a coauthor of *Essential Career Skills for Engineers.*

CHAPTER 1.3

EDUCATIONAL PROGRAMS FOR THE INDUSTRIAL ENGINEER

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In this chapter we present a historical overview of the development and evolution of higher education industrial engineering (IE) programs. Typical IE programs and their curricula are discussed in relation to the relevant quality assurance procedures that are emerging in connection with revised ABET criteria, the newly formatted PE examination, and public emphasis on program accountability in education. The influence on the IE curriculum of professionally related organizations such as CIEADH, CIE, and NSF is discussed. Perspectives on graduate studies, cooperative education, and the future of industrial engineering programs are also presented. Finally, we evaluate both the strengths and weaknesses of current industrial engineering programs as they strive to maintain a competitive position in relation to the other engineering disciplines. The future emphasis of industrial engineering will be on production and manufacturing, although significant contributions by industrial engineers are also anticipated in the service and logistics industries.

INTRODUCTION

In 1994, the Engineering Deans Council formally called for a redesign of engineering curricula nationally, and industry leaders supported the deans' position by pledging to actively recruit the graduates trained in the resulting new curricula [1]. Even before this occurred, a variety of sources had begun sending the message to the industrial engineering (IE) academic community that its students might not be adequately prepared and the industrial engineering discipline was entering a decline. This chapter examines some of the influences that have caused industrial engineering education to reach this state in recent years and discusses factors to be considered for assuring the vitality of the discipline in the future.

History of Industrial Engineering Programs

Interest in industrial engineering as an undergraduate field of study has grown steadily since the first industrial engineering course was designed and offered by Hugo Diemer in the

Department of Mechanical Engineering at the University of Kansas in 1901. For the majority of industrial engineers in the early part of the century, the bachelor of science (B.S.) degree was the only formal postsecondary educational credential. The IE curriculum was largely focused on work design and measurement, plant location and layout, material handling, engineering economy, production planning and inventory control, statistical quality control, and linear programming and operations research [2].

Prior to World War II, industrial engineering programs typically grew from mechanical engineering departments, but after the war the advent of operations research, business management, and computers brought different perspectives and backgrounds to bear on industrial engineering education. Concurrently, faculty members in other disciplines, such as business, applied mathematics, statistics, and computer science, viewed some of the newer industrial engineering subjects as separable from industrial engineering. Thus many academic disciplines became involved in, and felt ownership of, the areas of management science and operations research. The Institute for Operations Research and the Management Sciences, previously known as the Operations Research Society of America (ORSA) and The Institute of Management Science (TIMS), attracted engineering faculty members interested in these emerging subjects. Human factors and industrial psychology also entered industrial engineering programs during these years. A summary of the history of industrial engineering education can be found in Emerson and Naehring [2].

According to Tompkins, in 1978, 4.5 percent of the B.S. degrees awarded in engineering were in industrial engineering; in 1990 that proportion had grown to 6.5 percent [3]. Whereas in 1978, approximately 8.6 percent of M.S. and 3.8 percent of Ph.D. degrees in engineering were in industrial engineering, in 1990 those proportions had changed slightly to 9.2 and 3.7 percent, respectively. According to Turner, Mize, and Case, before 1960 fewer than 100 total doctoral degrees had been granted in industrial engineering [4]. By the mid-1970s, approximately 100 students received the doctoral degree each year; by 1997 that figure had grown to about 324 doctoral graduates per year in the United States. Table 1.3.1 shows the number of B.S., M.S., and Ph.D. degrees granted nationally each year in the past 10 years. Notice that in the last 10 years, the number of doctoral degrees granted in IE has doubled, but at the same time the number of bachelor's degrees has decreased by 20 percent.

Since 1990, undergraduate enrollment in the United States has generally declined. At the same time, new educational programs for the industrial engineer are being created around the world, particularly in Asia. Presently, there are more than 200 industrial engineering programs worldwide. Engineering colleges and universities in the United States have also been streamlining their academic programs since 1990. As a result, industrial engineering programs have been critically reviewed nationwide. Many have redirected their program emphasis to manufacturing systems while others have been merged again into the mechanical engineering discipline.

TABLE 1.3.1 Degrees Awarded in Industrial Engineering, 1988 to 1997

	Bachelor's	Master's	Doctoral
1988	4584	2140	149
1989	4519	2404	204
1990	4306	2387	200
1991	4295	2740	204
1992	4083	2856	231
1993	3689	3284	274
1994	3522	3418	294
1995	3520	3281	331
1996	3653	3462	317
1997	3628	3403	324

Source: The Engineering Workforce Commission of the American Association of Engineering Societies.

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Since industrial engineering programs outside the United States have largely adopted practices and curricula from the US, the discussions presented here can generally be extended to educational programs worldwide.

Industrial Engineering Definition

In 1955, the American Institute of Industrial Engineers (now the Institute of Industrial Engineers, IIE) adopted the following definition of industrial engineering:

> Industrial engineering is concerned with the design, improvement, and installation of integrated systems of men, materials, and equipment. Industrial engineering draws upon specialized knowledge and skill in the mathematical, physical, and social sciences together with the principles and methods of engineering analysis and design, to specify, predict, and evaluate the results to be obtained from such systems.

This definition formed the basis for the curriculum developed by the influential study supported by the National Science Foundation (NSF), which was documented in a 1967 publication by R. H. Roy [5]. Most present industrial engineering programs developed their curricula based on this report; as a result, graduates with this background form much of today's industrial engineering community.

The Roy Report

The Roy report described the objective of IE education as the preparation of students in the quantitative, economic, and behavioral ingredients and processes of analysis and synthesis in design and decision making [5]. The report provided an ambitious vision that has served as the model for industrial engineering curricula worldwide since its appearance. Remarkably, this philosophy was not extensively challenged until the past decade. The curriculum for the industrial engineering major advocated in the Roy report was as follows:

- *Liberal Studies:* Industrial engineering students were expected to be continuously engaged in liberal studies throughout the four years of study, but the report made no recommendations regarding the precise content of this portion of the curriculum.
- *Social Sciences:*

  Economics—every industrial engineering student was required to complete an introductory course in economics. The course was to be of one academic year's duration and was to cover both micro- and macroeconomics.
- Behavioral studies—according to the report, throughout the history of our profession the industrial engineer has been an "agent of change." The report states that the necessity for preparing engineers to deal with unstructured problems (both technological and behavioral) will continue to gain importance in the future.
- *Mathematics, Statistics, Probability:* The report recommended that the professional industrial engineer of the future have mathematical facility beyond that of his predecessors, possibly beyond that of his peers in other engineering disciplines.
- *Natural Science:* The report noted that with increasing frequency industrial engineers were also finding their way into various kinds of studies associated with biology and medicine. As a basic subject in natural science, biology could serve the industrial engineering students well, either as additional material or in substitution. In general, chemistry and physics would seem preferable as requirements but flexibility to make changes for those with special needs and interests should be possible.

- *Engineering Science:* Solid and fluid mechanics, thermodynamics, electrical science, statistics and dynamics, and material science have been recognized as engineering science; these five subjects are found in the curricula of different engineering majors in many institutions. All of these subjects are extensions of natural science; they have attained recognition as engineering science by virtue of their deductive and analytical content and their applicability to the solution of diverse engineering problems.
- *Industrial Engineering:* The following topics were believed to be *singularly* relevant to the education of professional industrial engineers and they constituted an industrial engineering core in the Roy report.

  Accounting.

  Engineering economic analysis.

  Computer science—all industrial engineering students must acquire computer skills in areas including problem solving, simulation, and especially data processing.
- Manufacturing Methods:

  Techniques—for a long time the hallmark of industrial engineering has been an array of subjects of great practical utility. Motion and time study, in a very real sense, have epitomized the instructional content of industrial engineering, along with wage incentives, job evaluation, production control, tool design, materials handling, plant location and layout, and statistical quality control.

  Systems analysis and synthesis—the industrial engineer should be familiar with the fundamentals of control systems and control theory, model building, network analysis, simulation techniques, and similar topics.

  Design—since the design and synthesis of the systems of people and machines are the mission of the industrial engineer, it is important for the curriculum to provide instruction in design and synthesis.

Table 1.3.2 summarizes the material recommended for each of the areas included in the Roy report curriculum.

Buzacott's Analysis

Criticism of the IE curriculum began to emerge in 1984 when J. A. Buzacott published his vision of the future of the industrial engineering discipline [6]. Quoting Porter's inaugural lecture of 1962 [7], Buzacott listed those characteristics that define the domain of industrial engineering:

1. Focus on formal organizations engaged in production
2. Concern with the interaction between management and engineering

TABLE 1.3.2 Core Curriculum for Industrial Engineering Majors Suggested by the Roy Report, 1967

	Semester courses
Liberal and social sciences, including economics	8 to 14
Mathematical sciences	7 to 9
Natural sciences	4
Engineering sciences	10 to 14
Industrial engineering	6 to 10
TOTALS	35 to 51

3. Commitment to creating improvement
4. Interest in the wider impacts of new technology

Buzacott raised a number of relevant issues, but perhaps his most serious charge was that although the Roy curriculum contained substantial academic content and provided a solid education for its graduates, it has not proved to successfully promote the development of industrial engineering as a discipline. The broad subject matter of the Roy curriculum all but guaranteed that IE departments would be poorly integrated organizations with differing perspectives, methods, and even conflicting values among the members because of the distinct differences between the areas of operations research, human factors, manufacturing, engineering economy, and management—and the practitioners of each.

Comments and Observations by Kuo and Deuermeyer

In spite of significant changes in the role and scope of activities of the industrial engineer in recent years, the basic IE curriculum has remained fairly constant since the 1950s. Fortunately, in the past few years a positive trend toward curricular reform has begun to emerge in universities across the United States. Educators universally express concern for enhancing the quality portion of the curricula and for improving the communication skills of students. All educators are interested in bringing the course content into better alignment with contemporary industry requirements.

The breadth of the old industrial engineering programs is not necessarily advantageous today. A problem with the traditional IE curriculum was lack of depth. Industrial engineering students typically sampled from a smorgasbord of courses—traditional IE courses plus a few courses in business and accounting. Hindsight shows that the balance between breadth and depth in the old curriculum was skewed. It is expected that the academic survivors in the next 10 years will be those departments with focused programs that will give students a sturdy foundation for entering the industrial environment.

Although the vision of industrial engineering defined in the Roy report was an ambitious and conceptually rich one, the way in which the typical curriculum evolved over time from this philosophical base has created problems that the academic IE profession has been slow to address. Over the past decades, industry and industrial practices have changed immensely. In Kuo and Deuermeyer's opinion, it is impossible to implement the curriculum recommended by the Roy report with sufficient depth in a four-year program because it contains too much emphasis on generic disciplines rather than how industrial problems relate to these disciplines [8]. Namely, the curriculum based on the Roy report has been too broad and too shallow in technical content. It has also been too slow in responding to industry's needs. Unlike other engineering disciplines, many industrial engineering subjects, with the exception of operations research, are not heavily calculus based. Students trained according to the Roy report's curriculum were likely to become general engineers.

The curriculum in industrial engineering proposed by the Roy report was not intended to be monolithic; on the contrary, it encouraged individual institutions to develop programs suited to their own resources, interests, and traditions. This approach led to the disciplinary diversity, which has been both an asset and a liability to the profession.

CONTEMPORARY EDUCATION PROGRAMS OF INDUSTRIAL ENGINEERING

Many accredited industrial engineering programs today offer courses in human factors and ergonomics, operations research, and manufacturing systems engineering. Human factors and ergonomics is more behavior oriented and tends to place emphasis on work physiology, although the recent trend has been on human-machine interaction. Human factors and ergonomics help to improve the usability of technology and the safety and quality of working and living environments.

Operations research has always been highly mathematical or statistical. Operations research methods are supposed to develop and analyze mathematical models of systems that incorporate factors, such as chance and risk, to predict and compare the outcomes of alternative decisions or strategies. Students who have taken courses in operations research learn to model complex systems, analyze system models using mathematical and statistical techniques, and apply the techniques to engineering problem paradigms. The resulting data help decision makers determine policy, allocations, and the best courses of action in the control of complex systems.

Manufacturing systems engineering focuses on the design, analysis, and control of integrated manufacturing systems. Manufacturing systems engineering provides students with the analytical and practical knowledge of manufacturing systems required for designing and integrating production, inventory, and quality control functions. It also provides students with functional knowledge of production equipment, materials handling, and assembly. Emphasis is on understanding the fundamental operating characteristics of manufacturing systems, improving the productivity of existing systems, and designing new systems that are both cost effective and need responsive. Manufacturing, which was traditionally associated with the metal cutting business, has evolved to include the design and analysis of integrated systems.

Typical Industrial Engineering Subjects

In addition to the basic engineering and science subjects recommended in the Roy report, the typical IE courses adopted as required core courses today include

- Capstone design
- Deterministic and stochastic optimization
- Engineering economy
- Ergonomics and workplace design
- Facilities design
- Inventory and production control
- Production/manufacturing systems
- Quality control
- Simulation

Other popular courses included in the industrial engineering curriculum are computer-integrated manufacturing (CIM), computer-aided design/manufacturing (CAD/CAM), engineering management, accounting, database management, and manufacturing processes. Recently, total quality management has been added to the required course list in many programs. These courses provide breadth, but most do not emphasize the necessity to apply the state-of-the-art technologies that drive industrial progress, including ever changing management practices. For example, quality and technology are more important concepts than cost accounting for staying competitive in today's industry, and they should receive more emphasis. Typical industrial engineering departments require at least 130 semester credit hours to complete four and a half years of a B.S. degree. However, the recent trend is to receive around 120 credit hours to finish the B.S. degree.

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Laboratory Component of Educational Experience

State-of-the-art laboratories are critical for preparing today's industrial engineers for jobs in industry. Some IE laboratories that typically enhance the modern IE curriculum include the following.

Computer Integrated Manufacturing Laboratory. This laboratory contains a fully integrated system consisting of full-scale machine tools, industrial robots, and a flexible material transport and storage system. These system components are physically linked with a computer network providing the interconnectivity necessary for systems level research.

Manufacturing Automation Laboratory. This laboratory provides support for courses in computer-integrated manufacturing, robotics, programmable automation, and material handling. Students are exposed to the software and hardware elements related to automated manufacturing.

Knowledge-Based System Laboratory. This laboratory can serve as a focal point of intelligent systems research, providing support for learning and application of expert systems technology and artificial intelligence techniques. The activities focus on systems design techniques, evaluation of development software, information systems integration, and development tools for concurrent engineering and agile manufacturing.

Industrial Automation Laboratory. This laboratory generally hosts a state-of-the-art electronic assembly cell that serves as a physical simulator. It consists of a multihead assembly module, mobile and fixed inspection stations, intelligent data collection module, and material handling systems. Activities conducted in the laboratory in electronic assembly include process planning, operational planning, and scheduling.

Computer Simulation Laboratory. This laboratory can help develop a teaching capability in manufacturing/simulation. Activity focuses on robust multisystems design. Since simulation and modeling now play a unique role in problem solving, industrial engineering students rely heavily on computer simulation.

Quality Laboratory. Techniques on design of experiments, quality cost, and design variation can be developed in this laboratory using manufactured goods such as electronic products or chemical processes. Depending on the applications, this laboratory can be either more computer oriented or processes oriented.

Laboratories specializing in ergonomics, work measurement, facility layout, and others are also important. Industrial projects from various companies can be incorporated into the student laboratory experience.

Cooperative Education

Another important component of the contemporary industrial engineering education experience for many students is the Cooperative Education Program (COOP). The COOP is a planned and supervised program allowing students to gain valuable work experience and academic credits outside the classroom. Paid COOP work experience related to industrial engineering is designed to give students increased responsibility each work term. COOP works best when a well-designed degree plan is developed early in a student's academic program. Students typically alternate periods of school and work during the second, third, and fourth years while enrolled in school. Summer internships are often available for students to enjoy industrial work experience before graduation.

Many companies, particularly manufacturing companies, provide industrial engineering students with COOP opportunities. Benefits to the students from participating in COOP include gaining insight on job types, obtaining useful employment contacts, increasing motivation, adding relevance to the educational process, developing maturity and professional skills, providing added financial support, and earning a Cooperative Education Certificate. Furthermore, students who have had the COOP experience tend to find jobs more quickly and to earn a higher starting salary upon graduation. Providing COOP opportunities to industrial engineering students benefits the companies by offering a rich source of manpower, providing an infusion of ideas from enthusiastic students, ensuring continuous job coverage, exposing students to business concepts and corporate culture, enhancing community image, and reducing training costs after recruitment. On the university side, the COOP program complements academic theory, extends the work setting beyond the campus, enhances graduate placement, and nurtures university-industry relations.

Extension Education and Distance Learning Programs

Lifelong learning is increasingly being recognized as important for personal and professional development and enrichment in all engineering fields. Good sources for seminars, conferences, and short courses are IIE, the American Society for Quality (ASQ, previously American Society for Quality Control), the Human Factors Society, the Society of Manufacturing Engineering, the Annual Reliability and Maintainability Symposium (RAMS), and others. Specialized subjects in industrial engineering, such as total quality management, work measurement, and simulation are offered at various major annual conventions and by private consulting firms. Continuing education units (CEUs) can be earned by taking these courses. Also many universities offer regular courses through a televised facility to industrial sites where students can earn credits towards a degree. Recently, distance learning courses have been offered by Internet and CD-ROM. The National Technological University (NTU) offers a large number of subjects through the televised media.

NATIONAL ORGANIZATIONS AND PROGRAM ASSESSMENT

A number of national organizations with close ties to the industrial engineering academic community affect practice and influence opinion in industrial engineering education. Often they help the discipline to identify issues of concern to the educational and industrial communities and to the public. One such topical concern is program assessment, which has become very important as a measure of accountability in education.

National Science Foundation

In 1984, the National Science Foundation created the Division of Design and Manufacturing (now Division of Design, Manufacture, and Industrial Innovation, DMI). Through rigorous peer and panel review processes, NSF has increasingly provided funds for industrial engineering faculty to perform science-based research in operations research, production, manufacturing, and design. In addition, DMI encourages industry-relevant research, sponsors projects with an educational component, and supports laboratory development projects. Special incentives have been provided to faculty who recruit undergraduates to participate in their NSF research projects.

Council of Industrial Engineering Academic Department Heads (CIEADH)

The Industrial Engineering Academic Department Heads in North America created CIEADH for the purpose of discussing and exchanging information about academic industrial engi-

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neering. Usually, CIEADH holds two meetings annually—one in the fall to discuss academic issues such as curriculum and the other one in the spring, concurrently with the IIE annual meeting, to review business related to student employment, department staffing, faculty salaries, benchmarking, and other administrative issues.

Other ways that CIEADH members influence trends in industrial engineering education is by recommending faculty representatives to serve as Accreditation Board for Engineering and Technology (ABET) visitors, providing questions for the Fundamentals of Engineering (FE) and Professional Engineering (PE) examinations, and suggesting ways to help improve ABET implementation. Although an independent organization, CIEADH interacts with IIE to jointly promote the industrial engineering profession.

Council of Industrial Engineering

The Council of Industrial Engineering (CIE) is an informational advisory group to IIE and its constituent groups and supports the profession and IIE's mission. Joint workshops sponsored by CIE and CIEADH have provided a forum for the exchange of information on emerging technologies and new practices, which impact the placement of industrial engineering students as well as curriculum development. In particular, CIE members have been instrumental in promoting the incorporation of modern industrial practices such as TQM, just-in-time, and supply chain management into the IE curriculum.

The Industrial Engineering Division of the American Society for Engineering Education

The IE division of the American Society for Engineering Education (ASEE) comprises members of ASEE who have interest in industrial engineering education. The IE division publishes an annual newsletter reporting recent developments in each of the accredited IE programs and holds its annual meeting in conjunction with the ASEE conference in June of each year. ASEE also publishes annually the productivity statistics of all IE departments in the United States.

Accreditation Board for Engineering and Technology

The Accreditation Board for Engineering and Technology is recognized in the United States as the sole agency responsible for accreditation of educational programs leading to degrees in engineering. The first statement of the Engineers' Council for Professional Development (now ABET) relating to the accreditation of engineering educational programs was proposed by the Committee on Engineering Schools and approved by the council in 1993. The original statement, with subsequent amendments, was the basis for accreditation until 2000. Adherence to the new criteria, entitled "Engineering Criteria 2000," will be required of all programs in 2001 [9], although some universities have already requested program evaluations using Engineering Criteria 2000.

The creation of ABET assured the public that engineering programs meet certain threshold standards of content and that graduates have educational experiences that are consistent. ABET accreditation of engineering programs is important because graduation from an Engineering Accreditation Commission (EAC) accredited engineering program is usually a requirement for eligibility to sit for the Fundamentals of Engineering Examination; it can also be important if an engineering student wishes to transfer to a different institution.

ABET is supported by 22 participating bodies, one of which is IIE, 6 affiliate bodies, and 1 Cognizant Technical Society. It consists of a board of directors, the Engineering Accreditation Commission, the Technology Accreditation Commission (TAC), and the Related Accreditation Commission (RAC). An executive director of ABET reports to the board of directors and there are accreditation directors for the EAC and the TAC as well as staff to support the accreditation processes.

The development of criteria for engineering and engineering technology programs is a shared responsibility and it consists of two parts. The general criteria define the basic requirements for all degrees in engineering or engineering technology; program criteria address the requirements for disciplinary specific degrees such as the B.S. in industrial engineering. The general criteria have evolved through the combined efforts of education committees in the participating committees, which culminate in recommendations to the board of directors by a cognizant commission, such as the EAC. The nature of the general criteria include one year of an appropriate combination of mathematics and basic sciences, one-half year of humanities and social sciences, and one and one-half years of engineering topics including subjects in the engineering sciences and engineering design. Program criteria are the responsibility of the cognizant participating body but are reviewed and recommended by the appropriate commission for approval by the board. Proposed criteria changes are published for comment from the engineering community for a period of more than one year before being approved by the board.

ABET accredits individual programs rather than institutions. A program wishing to be accredited invites ABET to make an accreditation visit. The institution prepares a set of comprehensive self-study documents providing information about its engineering curricula, faculty, student admissions and graduation requirements, facilities, laboratories, computer networks, and financial support. ABET appoints an accreditation visiting team consisting of a chairperson from the EAC and a representative for each engineering discipline being evaluated. This team visits the campus, meets with faculty, students, and administrators, and examines the facilities and reviews examples of student work. After appropriate due process an accreditation action is voted by the EAC: The maximum length of accreditation is six years. At the end of the 1995 to 1996 accreditation year cycle, there were 1516 accredited engineering programs at 315 institutions. Of these, approximately 97 are industrial engineering or closely related programs. For the TAC there were 436 associate and 324 bachelor degree programs at 250 institutions.

Under Engineering Criteria 2000, institutions seeking accreditation of an engineering program need to demonstrate clearly that the program meets the specific criteria in the following areas:

1. Students
2. Program educational objectives
3. Program outcomes and assessment
4. Professional component
5. Faculty
6. Facilities
7. Institutional support and financial resources
8. Program criteria

Outcomes Assessment

The new ABET 2000 accreditation requires institutions to document student learning outcomes. Although there is no definite format mandated by ABET, some suggested ways to conduct outcome assessment are:

1. Conduct senior exit interviews and follow up on the graduates' careers, including graduate school, for three to five years after graduation. Questions should include usefulness of

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the courses taken in the institution, strengths and weaknesses of the curriculum, and comments on the quality of course instruction. The next step is benchmarking graduates' progress with graduates from other industrial engineering programs, other engineering disciplines, and other related fields.

2. Require graduating seniors to take the FE examination and record their passing rate. Note that students taking the examination are not required to pass in order to receive the degree at most institutions.

3. Require graduating seniors to take the Graduate Record Examination (GRE) Advanced Subject and record their results.

4. Perform a program review, conducted by an external committee consisting of members from other institutions and industry. Such a process involves interviewing faculty and students, and benchmarking the visited program with others. A report is expected at the completion of the review. This kind of review is different from the ABET review in that it is formative, rather than summative, in intent.

5. Visit with the companies that have recruited graduates during the past 5 years. Treat the companies as the customers of the institution. Also, interview other institutions about the quality and performance of the program's graduates who are admitted to graduate school.

Fundamentals of Engineering Examination and the Professional Engineering Registration

The Fundamentals of Engineering (FE) examination (formerly the Engineer-in-Training exam) can be the first step toward registration as a professional engineer. Professional engineering registration is the only practicing engineering credential that is recognized across disciplines [10].

The topics on the morning FE test cover the first two years of an accredited engineering curriculum: chemistry, computers, dynamics, electrical circuits, engineering economics, ethics, fluid mechanics, material science/structure of matter, mathematics, mechanics of materials, statics, and thermodynamics. The general afternoon test has recently been replaced with discipline-specific examinations, each aimed at the last two years of an accredited curriculum, with the examinees choosing from one of the following options: chemical, mechanical, electrical, civil, and industrial engineering. The general examination is still used for other disciplines. There are 20 topics to be covered in the industrial engineering afternoon test; they include cost analysis, computations and modeling, engineering economics, ergonomics, engineering statistics, design of industrial experiments, facility design and location, information system design, industrial management, manufacturing processes, manufacturing systems design, material handling system design, mathematical optimization and modeling, productivity measurement and management, production planning and scheduling, statistical quality control, total quality management, queuing theory and modeling, simulation, and work performance and methods.

Other Program Evaluations

Every 10 years, the National Research Council (NRC) conducts a thorough study of all research doctoral programs, including industrial engineering, in the United States. The most recent report by NRC was published in 1995 [11]. Table 1.3.3 lists the 20 industrial engineering Ph.D. programs rated highest by NRC. *U.S. News & World Report* conducts annual studies on the undergraduate and graduate program rankings in many disciplines. These two surveys have had the most influence in recent years on the public perception of an individual program's reputation.

TABLE 1.3.3 Twenty Highest-Rated Industrial Engineering Ph.D. Programs, 1995

1.	Georgia Tech
2.	University of California-Berkeley
3.	Purdue University
4.	University of Michigan
5.	Texas A&M University
6.	Northwestern University
7.	Stanford University
8.	Virginia Tech
9.	Penn State University
10.	University of Wisconsin-Madison
11.	North Carolina State University
12.	Ohio State University
13.	University of Illinois at Urbana-Champaign
14.	Rensselaer Polytechnic Institute
15.	Lehigh University
16.	Oklahoma State University
17.	Arizona State University
18.	State University of New York-Buffalo
19.	University of Florida
20.	Auburn University

Source: The National Research Council, 1995.

TRENDS IN THE FUTURE

Commitment to production and manufacturing systems engineering is the key to competitiveness in the global marketplace. The industrial engineer can contribute significant expertise and leadership in both of these areas.

Characteristics of the Future Curriculum

Industrial engineering education in the future needs to train students for a particular disciplinary niche. According to Kuo and Deuermeyer [8] the curriculum of the future will

1. Be more problem-driven than tool-driven.
2. Achieve vertical integration of subjects and design concepts.
3. Be relevant to industry.
4. Emphasize quality and information concepts, based on a systems approach with an industrial component.

Manufacturing and Production Systems—Trend of the Late 1990s

A positive trend on the industrial scene is the current emphasis on manufacturing and production systems. Traditionally, engineers have designed a product or a system by looking at one thing at a time, figuring out the problems, and over several iterations, refining the product. The quality and reliability of a product or system has typically been determined after manufacture or after a system is in place.

For today's global markets, however, the traditional approach takes too long and is too costly. Even short production delays can mean loss of market share in today's highly competitive, highly specialized, and rapidly changing markets. Because it has become evident that their survival depends on it, many world industries are beginning to develop ways to catch up. Particularly in the high-technology industries, the competition is so intense, even within domestic markets, that only those companies who successfully get robust products to market ahead of the competition can expect to survive.

The heightened emphasis on manufacturing and production systems that has resulted from these competitive pressures offers real opportunity for the professional industrial engineer. Industrial engineers have an important role to play in all aspects and at all stages of the manufacturing and production process—first in the design phase by including quality, reliability, and cost effectiveness, and then by helping to optimize the efficiency and effectiveness of the entire manufacturing process.

Industrial Engineers for the Service and Logistics Industry

Many industrial engineering methods and techniques are generic in improving effectiveness and efficiency of systems operations. Others can be used to identify optimal solutions to large and complex system design problems. In addition to the many manufacturing system problems that industrial engineers are trained to solve, industrial engineers are also well equipped to approach many service-related problems. Like the curriculum in industrial engineering proposed by the Roy report [5], today's IE curriculum is not intended to be monolithic; on the contrary, individual institutions should be encouraged to develop programs best suited to their own resources, interests, and traditions. Some industrial engineering programs can, and should, put resources into developing programs for the service and logistics industry.

Some examples of industrial engineering applications in the service industry and the appropriately associated course work are listed here:

1. Health care industry: project management, computer applications, staffing and scheduling, simulation and modeling, quality and economic analysis
2. Transportation industry including the airlines industry: scheduling, safety, simulation, mathematical programming, network analysis
3. Utility or the distribution industries: project management, safety and quality, scheduling, management information systems
4. Government organizations such as the U.S. Postal Service: productivity improvement, quality management.
5. Other organizations such as science and technology, software industry, sales and marketing, and finance departments: industrial engineering concepts

Industrial engineers can contribute to many other service industries including the insurance business, which is multinational in nature and involves high value-added operations.

Future for Industrial Engineering Graduates

What does the future hold for an industrial engineering graduate? The current balance between supply and demand is excellent. Salary offers averaged $39,894 in 1998 for B.S. graduates nationwide [12].

Once on the job in the manufacturing sector, the industrial engineer can expect to work with other engineers, particularly those in mechanical, electrical, and computer engineering, as part of a team. The role of the industrial engineer is often to oversee the working of the manufacturing system as a whole and to develop ways to make the various components interact more efficiently and cost effectively. In the future, industrial engineers can also expect to work closely with software and hardware engineers as design specialists and design engineers.

To remain competitive, industrial engineers have to globalize their perspective. This means they need to view systems operation globally and to consider the life cycle and supply chain concepts when evaluating the production and supply system.

CONCLUSIONS AND SUMMARY

We have learned from experience that curriculum development should be a process that undergoes continuous evaluation and modification. Since industrial engineering is an applications-oriented engineering discipline, it is our duty as industrial engineering faculty and practitioners to bring the most up-to-the-minute technologies into our academic programs. Like other types of competitive businesses, industrial engineering programs need to be benchmarked, challenged, and assessed from time to time. Also in today's competitive world, every academic program needs to develop a market niche, based on a combination of market forces and the strengths of the individual program.

After a three-and-a-half-year study, a recently developed industrial engineering curriculum based on the problem-driven approach is now available at Texas A&M University. See Kuo and Deuermeyer for more details [8].

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EDUCATIONAL PROGRAMS FOR THE INDUSTRIAL ENGINEER

BIOGRAPHY

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Source: MAYNARD'S INDUSTRIAL ENGINEERING HANDBOOK

CHAPTER 1.4

THE INDUSTRIAL ENGINEER AS A MANAGER

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Because organizations have undergone and will continue to undergo significant change, the role of the industrial engineering manager is also changing. We are expected to be excellent technically and also to be coach, trainer, mentor, and facilitator. Often engineers are promoted to managers because of their technical skills. However, sometimes these skills get in the way. We need to sharpen our softer "people" skills for getting results through others by

- Using effective management styles and leadership behaviors
- Communicating effectively
- Creating motivating work environments

Effective managers also get results by using systematic processes for the work their teams perform whether they are solving problems, making decisions, planning, or prioritizing concerns. We need to manage not only *what* our teams do but also the *how* or processes by which they work. This chapter will bring clarity to our new roles not only as industrial engineering managers, but also as process owners, to maximize the robustness and value-added contributions to our organizations.

THE CHALLENGES OF MANAGEMENT

Four Skill Cornerstones

The traditional role of the industrial engineering manager is undergoing significant change in many of today's industries. This change is a result of an emphasis on the use of multifunctional teams and the matrixing of staffs onto these teams for projects. The result is a new role for the manager. This change mandates a shift in focus from content to process. Prior to this change, the focus was primarily on *what* was being worked on. Today, the focus is also on *how* the work can best be performed. To get results through others in today's organization, the industrial engineering manager requires expertise in four dimensions. These four skill cornerstones are (1) technical, (2) managerial, (3) leadership, and (4) process.

Technical skills represent the traditional trained engineering skills gained academically and by professional experience. Managerial skills are those administrative skills, that is, effective time management or project management necessary to orchestrate the effective use of resources (people, time, and money). Leadership skills often center on the soft "people" interpersonal skills required to motivate and work through others to get results. Often, this requires an aptitude for coaching, teaching, and mentoring. Finally, process skills require the industrial engineering manager to be the process owner for his/her department. As process owner, the manager must make sure department personnel not only have the right technical skills and tools, but also follow systematic processes in using these skills.

Value-Added Work

Most companies today are asking their workforce to do more with less, with a mandate to do it right the first time. We are all being asked to evaluate our contribution. Surveys of U.S. industries show that typically we spend only 25 percent of our time on value-added tasks, as shown in Fig. 1.4.1. These are the tasks that our customers pay us to perform. A major portion of our time is spent on non-value-added rework or unnecessary work. It is our obligation as effective managers to find ways to increase the value-added contribution of our teams.

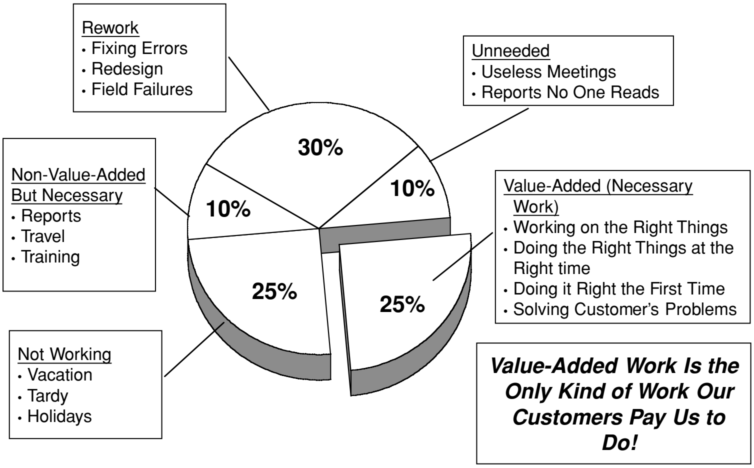

FIGURE 1.4.1 The concept of value-added work.

Think about your team's use of time. How much is truly value-added? Have your team take a self-audit of how they use their time. Next, brainstorm ways to increase their value-added effort. Focus on the effectiveness of their processes for finding the root causes of problems, making robust decisions, and creating plans that anticipate problems before they happen.

Challenges for the Industrial Engineering Manager

The challenge of increasing value-added contributions from you and your staffs is especially important for industrial engineering. Since your background and training is in a technical discipline, there is a high probability your technical skills gained you recognition as a potential leader or manager. Most companies equate technical excellence with leadership skills. However, a word of caution is necessary. Just because you were an excellent technical contributor does not guarantee you will be an effective leader. To the contrary, your technical skills may even get in the way of your ability to perform as a good manager. The first step to becoming an effective manager is to recognize the challenges you will face, some of which are listed as follows:

- *Setting goals and establishing priorities*—Being an effective manager mandates a change in roles for establishing objectives and priorities. The role of a leader requires the aptitude and skill for establishing clearly defined objectives that are meaningful, realistic, and measurable. Priority setting should consider the criteria of the seriousness, urgency, and future impact of the concerns facing you and your team on the job.
- *Management and motivational style*—Technical knowledge is no longer the sole deciding factor to achieving success. Odds are that your sharp technical skills got you recognized as a potential manager. As a manager or team leader, however, your behavior patterns become more important. Your management style in dealing with and motivating people may often play a more significant role in getting the right results than your technical skills.
- *New data*—The data you will be working with will be less familiar because they will no longer come just from the comfort zone of your area of technical expertise. Data will now come from the twilight zone of the unknown. The information you must process will come from all directions, some of it factual and some fictitious, some of it objective and some subjective. No matter how good your process is for analyzing information, you must make sure you are using factual, accurate data.
- *A new sense of urgency*—As a manager, you will be expected to get results *now.* Time is money, so you will have to solve problems quickly. Furthermore, you must be right the first time. You will have to make decisions on the spot with too few or often unclear data.
- *People problems*—Since one of your key resources is the people on your team, you will need the managerial skills to optimize their performance. Like production equipment or machinery, a worker's output can vary for many reasons. You will need new skills to solve people performance problems. These are the most difficult problems to resolve because the data will often come from opinions and not necessarily from observed behavior or facts.
- *No longer just one right answer*—As engineers, we have been trained to solve the equation—to find the one right answer. As managers, we need to understand there are many "right" answers or options to consider. The challenge is to select the best option depending on the circumstances. Often, the typical engineering approach is to continue to analyze until the job is 100 percent completed. The effective managerial approach often requires a decision with only 50 percent or less of the work done. A common trap for the engineer-manager is to fall into the analysis-paralysis mode, searching for the one right answer and wasting valuable time when a less than optimum solution will often suffice.
- *Delegating or working through others*—Your managerial role requires working with and accomplishing objectives through others. The three resources you manage are people, time, and money. Your accomplishments are only as good as the accomplishments of your people. A good manager asks not only "What have my people done for me today?," but also "What have I done for my people today to help them perform?"
- *Juggling multiple tasks and using your time wisely*—Management, by definition, requires that you have the ability to handle multiple assignments or tasks. To do this juggling effectively, you first need an approach for identifying and prioritizing concerns. Be sure your team is working on the right jobs at the right time. The use of your time will be different. You will be spending more time in meetings, making presentations, preparing, and reporting on your team's progress. Expect more scrutiny because you are responsible for more resources.
- *Process versus content*—The single biggest mistake of engineering managers, especially new managers, is the inability to understand the difference between the process and content issues of their jobs. As a result, the engineering manager will rely on his or her content knowledge.

This leads to a focus on what is being done rather than the process of how the work is done. An example is the engineer-manager who still attempts to perform the design without concern for how the design might better be performed (using best practice processes) by his or her team.

LEADERSHIP SKILLS AND PROCESSES

Your ability to handle these challenges will require the use of skills you may need to sharpen. One set of skills deals with the processes you use in handling the information of your job. The other set deals with core content leadership skills of knowledge used to get results by working through others. The relationship between these skills and process is shown in Fig. 1.4.2. The process skills focus on how you and your team go about solving problems, making decisions, planning, and identifying and prioritizing on-the-job concerns or issues.

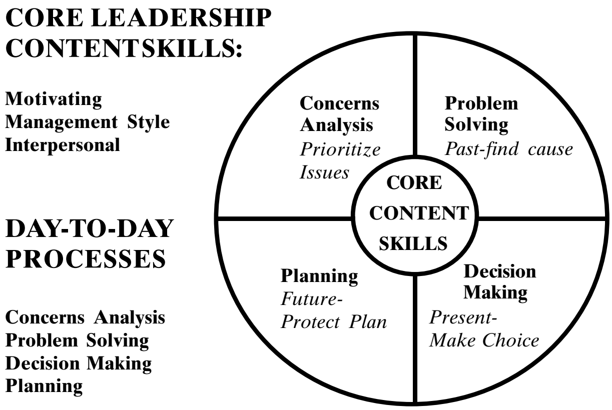
CORE LEADERSHIP
CONTENTSKILLS:
Motivating
Management Style
Interpersonal
DAY-TO-DAY
PROCESSES
Concerns Analysis
Problem Solving
Decision Making
Planning
Concerns Analysis
Prioritize Issues
Problem Solving
Past-find cause
CORE CONTENT SKILLS
Planning
Future-Protect Plan
Decision Making
Present-Make Choice

FIGURE 1.4.2 Leadership skills and processes.

Studies by Kepner and Tregoe, as described in their book *The New Rational Manager* [1], show that managers who get results do so by being systematic and logical. They follow a set of systematic processes in handling the data of their jobs. They recognize the need for a logical, sequential set of procedures in analyzing information. If you think about the tasks you perform on a daily basis, some of which are shown in Fig. 1.4.3, the common thread of all these activities is that they require you to process information. The raw materials of your job are the information you both receive and give day to day. How effective you are in processing this information determines your managerial effectiveness. However, no matter how good your processes are, if the information you work with is poor quality, then your results will be poor.

SYSTEMATIC PROCESS SKILLS

The use of a systematic process for analyzing information is analogous to the sequential, clearly defined process steps used by any successful manufacturing operation. In order to produce a quality product, one must start with quality raw materials and then follow a series of manufacturing steps in proper order.

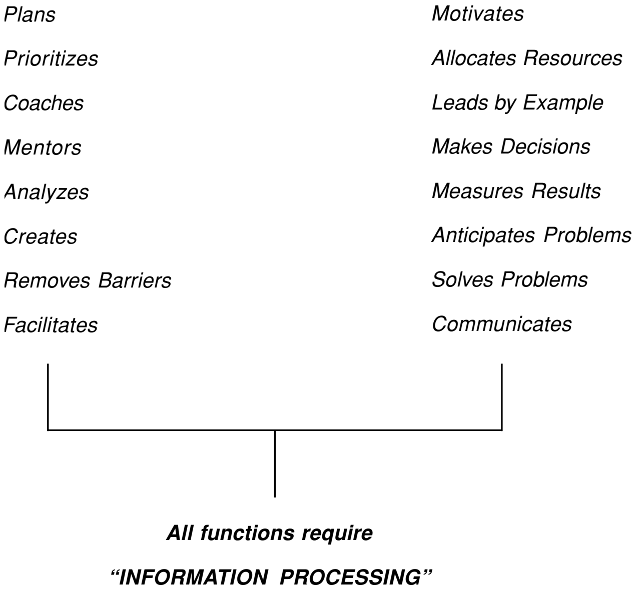
Plans
Prioritizes
Coaches
Mentors
Analyzes
Creates
Removes Barriers
Facilitates
Motivates
Allocates Resources
Leads by Example
Makes Decisions
Measures Results
Anticipates Problems
Solves Problems
Communicates
All functions require
"INFORMATION PROCESSING"

FIGURE 1.4.3 Management requires information processing.

There are simple questions you can ask yourself to determine how effective you and your team are in processing the data of your job: Can you list the steps that you use in solving a problem, or making a decision, or planning? Does everyone on your team follow the same set of steps? In your next meeting at work, ask the attendees what steps they use. Do they, for example, all follow the same problem-solving or decision-making process as a team, or do they flounder by taking a "random walk"? A lack of process is one of the main causes contributing to ineffective and inefficient meetings. In the following sections, we will discuss these important process skills.

Problem-Solving Process Skills

Many industrial engineering staffs spend over 50 percent of their time solving problems, and therefore need an effective set of problem-solving skills. Accurate problem solving is difficult for many reasons:

- Not enough information.
- Data is confusing.
- Not enough time.
- Biased opinions.
- Minds already made up on the answer.
- Inaccurate data.
- Problem not clearly defined to start with.
- Resources inadequate.

- Problem comes and goes.
- We jump to cause.
- Band-Aid fixing never leads to true cause.
- Too complex.

The first step is to determine the type of problem we must solve. The type of problem will determine the process we should use. Typically, there are four types of problems:

1. It never was right to begin with.
2. Something went wrong (field failure).
3. Find a better way.
4. People problems.

Each type of problem requires a unique problem-solving process as summarized below:

Problem Type #1: It Never Was Right to Begin With

- Actual condition historically unacceptable.
- May be caused by several factors.
- Brainstorm causes using Cause-and-Effect (fishbone) Diagrams.
- Prioritize causes using Pareto techniques.
- Develop countermeasures to eliminate high-priority causes.

Problem Type #2: Something Went Wrong (Field Failure)

- Starts with an acceptable *should* condition.
- An unacceptable *actual* condition (failure) then occurs.
- Problem quantified by a deviation between the should and the actual.
- Define difference between where the problem *is* and where it could be but *is not.*
- List and date changes to the *is.*
- Hypothesize causal statements by considering both differences about and changes to the *is.*
- Select the best causal statement (the one that fits the *is* and *is not* data with the fewest assumptions).
- Define actions to prove you have found the true cause of the defect.

Problem Type #3: Find a Better Way

- Starts with a condition, product, or service that needs improvement.
- Develop ideas using creative, nonlinear brainstorming techniques.
- One technique for brainstorming is Forced Connections. First list the functions the product or service must perform. Then brainstorm alternative ways to perform each function. Create a matrix of alternatives for each function and connect the alternatives in various combinations to create concepts.
- Define criteria (musts and wants) to evaluate the alternative concepts.

Problem Type #4: People Problems. The ability to solve people problems requires a special understanding of motivation, management style, and interpersonal skills and tactics that comes from knowledge of these core content skills:

- Recognize that people absorb change and may only exhibit poor performance much later than when the critical change went into effect.

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- Understand motivational needs.
- Use either the Rational Problem-Solving process or Cause-and-Effect techniques to identify possible causes.
- Remember that typically less than 10 percent are caused by the “inner person” (bad attitude).
- Identify causes by first exploring the five causal categories (resources, skills, information, consequences, and leadership) we can control, as shown in Fig. 1.4.4.

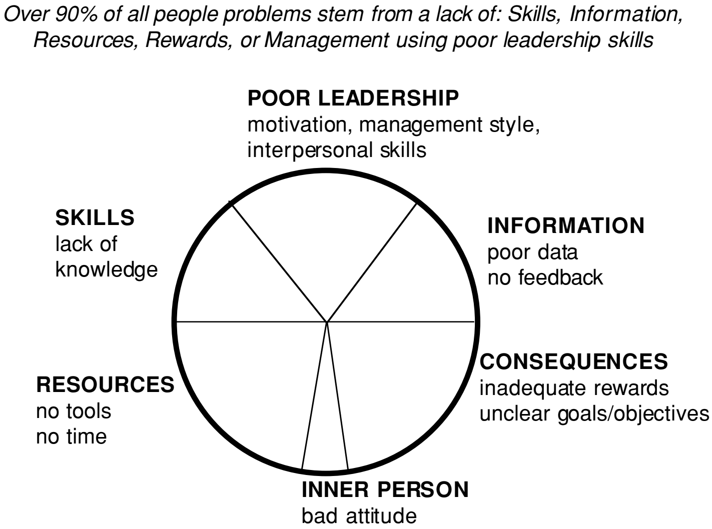
Over 90% of all people problems stem from a lack of: Skills, Information, Resources, Rewards, or Management using poor leadership skills
POOR LEADERSHIP
motivation, management style, interpersonal skills
SKILLS
lack of knowledge
INFORMATION
poor data
no feedback
CONSEQUENCES
inadequate rewards
unclear goals/objectives
RESOURCES
no tools
no time
INNER PERSON
bad attitude

FIGURE 1.4.4 Causes of people performance problems.

Decision-Making Process Skills

Once a problem has been solved, the next logical step to assure its proper resolution is to decide what to do. For example, in field failure types of problems, we must decide on corrective actions. For creative problems, we need to select the best alternative approach. We need a rational (linear, step-by-step), systematic decision-making process to assure we have selected the best possible approach or action. Decision making can be difficult for many reasons:

- Not enough information.
- Not enough time.
- Biased opinions.
- Alternatives have too many risks.
- Risks not considered before making the decision.
- Too few alternatives.
- Criteria undefined.
- Changing or unclear objectives.
- Conflicting objectives.
- Inaccurate data.

Peter Drucker, in his book *The Effective Executive* [2], lists what he considers to be the five most significant skills of successful managers. One of these is the ability to consistently make good decisions. The systematic decision-making process shown in Fig. 1.4.5 is a good approach to use in making good decisions. It will also help address many of the difficulties listed above. The process is based on establishing first the level of the decision, next the criteria to be used for the selection, and then the listing and ranking of candidates. Finally, a risk analysis should be performed on the top candidates before making the final choice.

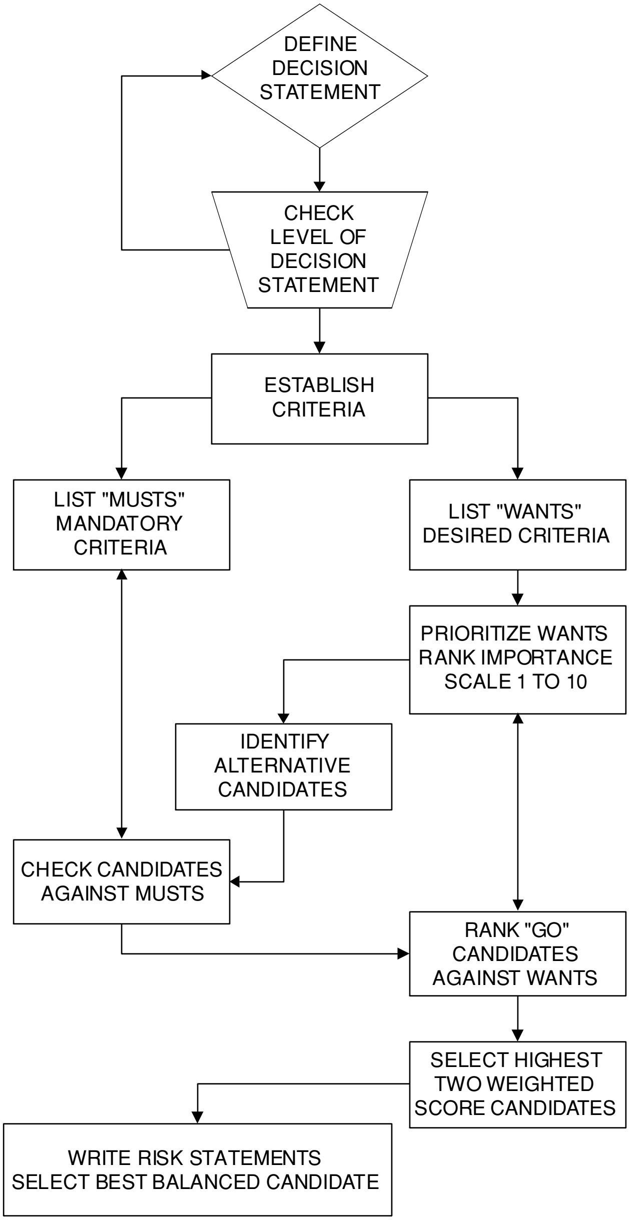
DEFINE DECISION STATEMENT
CHECK LEVEL OF DECISION STATEMENT
ESTABLISH CRITERIA
LIST "MUSTS" MANDATORY CRITERIA
LIST "WANTS" DESIRED CRITERIA
PRIORITIZE WANTS RANK IMPORTANCE SCALE 1 TO 10
IDENTIFY ALTERNATIVE CANDIDATES
CHECK CANDIDATES AGAINST MUSTS
RANK "GO" CANDIDATES AGAINST WANTS
SELECT HIGHEST TWO WEIGHTED SCORE CANDIDATES
WRITE RISK STATEMENTS SELECT BEST BALANCED CANDIDATE

FIGURE 1.4.5 Decision-making process flow chart.

Step 1. Define the Decision Statement. This "book title" is a one-line statement of what concern or issue will be resolved by making the decision. Always include an action verb (e.g., select or choose) to help identify this issue as a decision-making concern.

Step 2. Check the Level of the Decision Statement. Consider the level or range of alternatives that can be considered. Often the decision statement inadvertently limits the alternatives that can be considered. For example, a decision statement to "hire an engineer" precludes the alternatives to promote from within or subcontract the work. A higher-level (allowing more alternatives to be considered) decision statement might be to "obtain an engineer."

Step 3. Establish Criteria. List all factors that will be considered. Consider the resources available now and in the future (e.g., people, time, and money), as well as past experiences. Factors must be realistic and measurable (either on an absolute scale—e.g., "Have at least ten years' experience"—or relative—e.g., "The more experience the better").

Steps 4 and 5. Decide Which Are "Musts" and Which Are "Wants." Decide which factors are mandatory ("musts") and which are desired ("wants"). The musts have to be measurable on an absolute scale and will serve as a "go/no go" filter. The candidate will either pass the must requirement or will automatically be eliminated from selection. The wants will be measurable on a relative scale. They are used for comparison and ranking of two or more candidates who first passed the must filter. The wants will allow the candidates to be evaluated relative to each other.

Step 6. Prioritize Wants Criteria. List all wants criteria in order of importance. The most important factors always receive a value of 10. Factors of lesser importance receive a value from 9 down to 1. Equally important factors receive the same value. If all criteria were of equal importance, they would all receive a value of 10.

Step 7. Identify Candidates. List candidates, considering the level of the decision statement.

Step 8. Check Candidates Against Must Criteria. Determine their viability by checking to see that each candidate passes the must go/no go filter. If a candidate does not pass all of the must requirements, that candidate is a "no go" and is not considered any further.

Step 9. Rank "Go" Candidates Relative to Each Other Against Want Criteria. Starting with any single want parameter, compare candidates to each other to determine a relative ranking. The candidate(s) that best meets the want parameter receives a score of 10. Other candidates, depending on how close they are in comparison to the best candidate(s), receive a score ranging in value from 9 to zero. After ranking all viable candidates by this scoring system, multiply each score number (zero to 10) by the priority value (1 to 10). Add the sums to obtain the weighted score (ranging from zero to 100) for each candidate. The highest total is the "best relative choice."

Steps 10 and 11. Select Highest-Weighted-Score Candidates and Write Risk Statements. Select at least the two highest-scoring candidates and define what risks are associated with each. We will borrow a technique from failure modes and effect analysis (FMEA) to assess the risks. This is done by ranking the probability of the risk event happening—using a ranking of high (H), medium (M), or low (L)—and the severity of the consequences of the event—again using H, M, or L. Any risk that has an H-H ranking is most likely to happen and the consequences will be severe. Such risks must be considered before making the final choice. Always write risk statements in "*if* . . . *then*" sentences (i.e., "*If X* happens, *then Y* is the consequence"). An example of a high-risk statement is: "*If* our supplier XYZ fails to deliver on time (H), *then* our company will not meet its contractual commitments to our customer (H)." Because both the probability and severity of the risk are assessed as H (high), we need to consider this risk before deciding on selecting supplier XYZ. Thus, the risk assessment becomes part of the decision-making process. Unfortunately, we often leave risk assessment to the planning process *after* we have already made the decision.

Step 12. Select the Best-Balanced Final Candidate. Considering both the relative ranking (weighted total scores) and the risk analysis, select the best final choice. Even though a candidate may have the highest-weighted score total, there may be too many high-probability–high-severity risks associated with that candidate. At this point you have the choice to either accept the second-ranked candidate (provided its risk level is acceptable) or restart the decision-making process by identifying and evaluating a new group of candidates.

The following list discusses ways to use techniques from this decision-making process on your job:

- Make important decisions and recommendation presentations visible.
- When pressed for time and using only "partial process," consciously decide what steps to delete by assessing the importance of the data these steps could provide.
- Require your entire team to use the same process for decision making. Keep them in process, don't let them deviate, and your team will get better results with everyone playing by the same rules.
- Involve your team in decision making where it impacts them.
- Use decision-making (DM) process with client/customer/someone else to gain agreement.
- Map out a project with (go/no go) decision checkpoints (using must and want criteria) before taking the next step.
- At the next critical decision, ask, "Are the criteria for this decision clearly defined?," "Are they logical?," Is the level of the decision statement correct?"
- Use the must criteria list to make sure all candidates are viable such that a substandard candidate is never considered further.
- Develop a habit of writing at least one *if-then* risk statement for every important future action or activity.
- Use the DM process to establish criteria before interviewing job candidates.

Planning Process Skills

The next logical step after making a decision is to lay out a plan to implement the decision. The planning activity is difficult for many reasons:

- Never enough time.
- Once a plan is done it becomes obsolete.
- Planning is a boring job.
- Resources always are changing.
- Difficult to anticipate change.
- Cannot predict the future.
- Priorities always changing.
- No one follows the plan.
- The good planner is never recognized or rewarded.
- No interest.
- People are skeptical of the value of the effort put into planning.

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There are numerous benefits to using a systematic process for planning:

- Identify potential problems and risks before they occur.
- Take preventive actions before the problems arise.
- Set contingencies for the future.
- Prioritize future problems.
- Keep resources within the budget.
- Reduce non-value-added activities (rework, fixing errors).
- Control rather than react to the future.
- Attain our goals.

Several project planning and project management techniques and tools are available today. Yet the one aspect that needs emphasis is "how to protect the plan." The traditional planning process is predicated on success. We typically schedule tasks either sequentially or in series with the assumption they will be completed on time and within budget. Very often, when one task falters, then the entire plan becomes jeopardized. We need a process that will help us to anticipate what could go wrong and then help to prevent that from happening. The following systematic plan-protection process, as shown in Fig. 1.4.6, is intended to help you protect your plan (it starts with first having completed the planning of tasks to attain a plan goal):

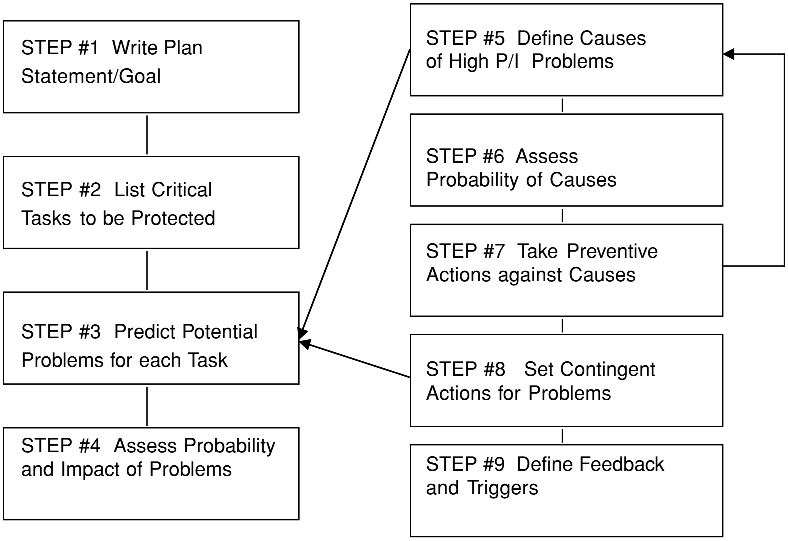

STEP #1 Write Plan Statement/Goal
STEP #2 List Critical Tasks to be Protected
STEP #3 Predict Potential Problems for each Task
STEP #4 Assess Probability and Impact of Problems
STEP #5 Define Causes of High P/I Problems
STEP #6 Assess Probability of Causes
STEP #7 Take Preventive Actions against Causes
STEP #8 Set Contingent Actions for Problems
STEP #9 Define Feedback and Triggers

FIGURE 1.4.6 Plan-protection process flow chart.

Step #1. Define Plan Goal. This book title describes the overall goal of the plan (e.g., *Deliver Production Lot #1 by 1Q*).

Step #2. List Critical Tasks. After having laid out all the tasks (their sequence and timing and interrelationships), identify the most critical tasks. These are the ones that, based on your team's experience, are most difficult to accomplish or are most critical to the success of your plan. These are the tasks that must be protected. You may uncover some valuable data about your project by doing so. Look for those tasks that may be more critical than others because of the

- Difficulty of the task
- Resources limited
- Resources required
- Threats
- Weaknesses
- Prior bad experience
- Impact of tasks not getting done

Step #3. List Potential Problems. For each task you wish to protect, list those future potential problems that could prevent that task from being accomplished.

Step #4. Prioritize Problems. Prioritize each problem with a high (H), medium (M), or low (L) ranking for

1. The *probability* (P) it will happen
2. The *impact* (I) or consequence of it if it does happen

Step #5. Identify Causes. For a problem with a high probability (P) and high impact (I), list the various possible causes that could make that problem happen.

Step #6. Determine Probability of Causes. Assess which possible causes have a high (H), medium (M), or low (L) probability (P) of happening. For those causes with a high probability, do Steps #7 and 8.

Step #7. Brainstorm Preventive Actions. Take preventive actions (do something now to prevent the cause).

Step #8. Brainstorm Contingencies. Set up contingent actions (something to be done in the future to minimize the consequences of the problem if it does happen).

Step #9. Define Feedback/Trigger Data Points. Set up data milestones (feedback to monitor progress of the critical steps) and triggers to set off the contingent actions if a problem does occur.

The following ideas are ways to use the process of "plan protection" on the job:

- Never approve a plan that is not protected (risks identified with both preventive and contingent actions).
- Make sure goals are well thought out—singular, attainable, measurable, and meaningful.
- Plan more effective meetings by using a meeting checklist—purpose, start time, time to complete, who will attend, what process will be used, what process steps will be followed, what data to bring, expected outcome.
- Set time each week to perform planning and plan protection with the goal to increase planning time and reduce non-valued-added problem-solving time.
- Encourage your team to take risks but first always ask if the risks (potential problem areas) have been identified and what has been done to protect against them.
- Make sure to always compliment/reward the good planner and not just the star problem solver.

- For every new project, make sure at least the single most critical task is identified and that a protection plan is developed for that task.
- Assess risks and potential problems by the probability (P) that they will happen and the impact (I) or severity of the consequence if they do. Use a ranking for both (P) and (I) of high (H), medium (M), or low (L).

Concerns Analysis Process Skills

A continuous challenge facing the industrial engineering manager is that of correctly identifying and prioritizing issues and concerns. It is important that the right things are being worked on at the right time. It is equally important that there is consensus between management and the team as to the importance and priorities of this work. This is often a difficult task for the following reasons:

- Conflicting priorities.
- The concerns or issues are too complex.
- Too easy to suboptimize.
- Unclear starting point.
- Concern is not clearly defined or quantified.
- Criteria to prioritize undefined.
- Nonmutual objectives.
- Some issues are long-term with unclear consequences.
- Not everyone agrees.
- Resources inadequate.
- Must cross functional boundaries.

We need a systematic process to help identify, clarify, and prioritize concerns that at the same time minimizes these difficulties. The following "concerns analysis" process, as shown in Fig. 1.4.7, is a good technique for this purpose. By using this technique you will be able to

- Clearly identify concerns
- Determine the type of concern
- Easily gain consensus on the priority of concerns
- Motivate your team by involving them in this prioritization process
- Start on an action plan to resolve the top priority concerns

The steps in using this process are

Step #1. List Concerns. Ask your team to identify those concerns or barriers they face in their job. This is one of the basic philosophies of effective management styles—to ask not only "What has my team done today?" but "What can I do (by breaking down barriers and addressing their concerns) to help them perform?"

Step #2. Check Concerns. Check the concern to make sure it is real, job-related, and important enough to spend resources on to resolve.

Step #3. Determine Type of Concern. Make sure the concern is clearly enough defined that the team knows whether it requires problem solving, decision making, or planning. The type of concern will determine the type of information required to resolve the concern. The type

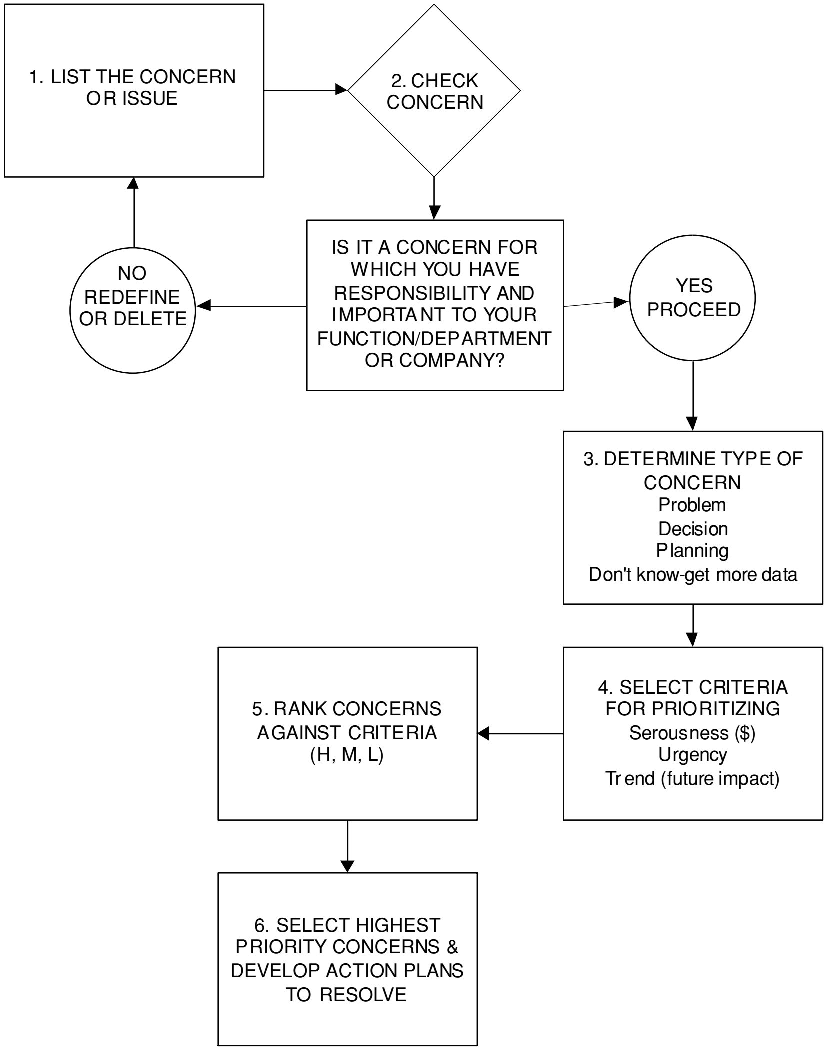

1. LIST THE CONCERN OR ISSUE
2. CHECK CONCERN
IS IT A CONCERN FOR WHICH YOU HAVE RESPONSIBILITY AND IMPORTANT TO YOUR FUNCTION/DEPARTMENT OR COMPANY?
NO REDEFINE OR DELETE
YES PROCEED
3. DETERMINE TYPE OF CONCERN
Problem
Decision
Planning
Don't know-get more data
4. SELECT CRITERIA FOR PRIORITIZING
Serousness ($)
Urgency
Trend (future impact)
5. RANK CONCERNS AGAINST CRITERIA (H, M, L)
6. SELECT HIGHEST PRIORITY CONCERNS & DEVELOP ACTION PLANS TO RESOLVE

FIGURE 1.4.7 Concerns analysis process flow chart.

will also dictate the type of process to be used to process the information of the concern and bring it to a successful resolution.

Step #4. Prioritize Concerns. The three most common criteria for prioritizing concerns are seriousness, urgency, and trend. Seriousness assesses the financial impact if we don't address the concern. Seriousness can be measured by lost sales or profits. Urgency considers the timing with which the concern must be resolved. Urgency is high, for example, if the customer or boss says it must be done now. Trend assesses what future consequences we will suffer if we don't address the concern today—for example, lost market share or dissatisfied customers.

Step #5. Rank Concerns. Be sure to rank concerns against each other using one criterion at a time. For example, if we had a list of concerns, we would rank them against each other first as to the seriousness. A few will most likely be high, some low, and the balance medium.

Step #6. Identify Highest Priority Concerns. Select the top-priority concerns. Typically, from a list of several concerns, some of them will be H-H-H and therefore of highest priority. These are the ones that deserve an immediate action plan to resolve.

LEADERSHIP SKILLS

There are several core content people leadership skills, as described by Jay Hall in reference [3], that the industrial engineering manager must master. These people skills are even more important in today's changing organizations. Organizational restructuring with an emphasis on teaming and matrix assignment across functional boundaries makes these skills mandatory.

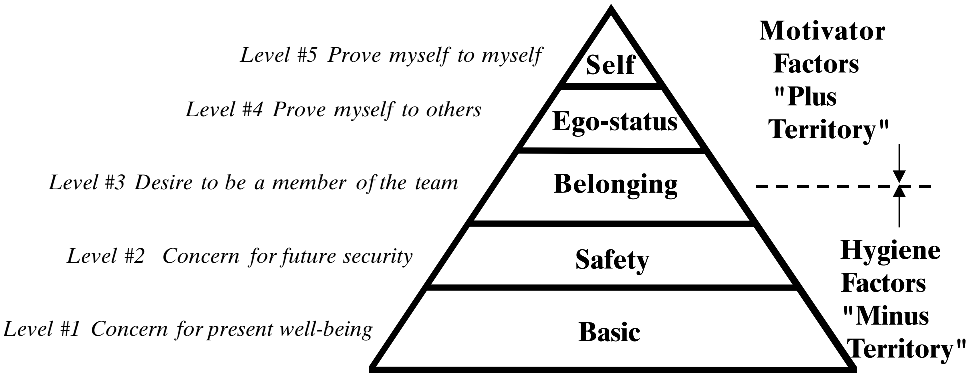
Three of the most important people skills can be classified as (1) motivating skills, (2) management style skills, and (3) interpersonal/communication skills. These are skills for which engineers typically receive little or no formal education. Most often these are skills learned on the job. Unfortunately, they may be learned from people or situations that are not always ideal role models. Each skill requires that we learn and become expert in content knowledge, i.e., the theories behind the skill. Next, we need to find ways to effectively apply the theories to our own specific on-the-job situations. The following information will highlight the theories behind each of the three skills, including a list of tips on how to apply the concepts to your job.

Motivating Skills

One of your functions as a manager is to find ways to motivate your team. Establishing a motivating work environment is one of the trickiest tasks you will face. This is because different things motivate each of us. So a blanket policy or standard set of procedures to motivate a group will often fall short for many of the group members. Following are some tips for structuring an effective motivating work environment for your group: you must

- Analyze your own beliefs about motivating
- Understand the "staircase of needs" concept
- Be creative in configuring job designs and descriptions
- Emphasize higher-level needs
- Determine team members' needs, goals, and desires
- Structure assignments to meet both employees' and the company's goals
- Aim to continuously raise the level of motivators up to the Recognition and Ultimate Self levels

Research by Maslow [4] and Herzberg [5] determined that each of us has varying needs that must be fulfilled before attaining true job satisfaction. There are five levels of needs as shown in Fig. 1.4.8. We all start with the lower-level needs of Basic Self and Self-Security. Once these needs are adequately met, then we are able to move up the ladder or hierarchy of needs to the Relationship level and finally to the Recognition and Ultimate Self levels. True job satisfaction can only be attained by first satisfying the lower-level needs before moving to the higher-level needs. Herzberg refers to the lower-level needs (Basic and Security) as hygienic. If not fulfilled, they can lead to job dissatisfaction. If fulfilled, they only take away dissatisfaction. Only by fulfilling these lower-level needs, can we move up the hierarchy to the Relationship, Recognition, and Ultimate Self needs. If these are not fulfilled, there is a lack of job satisfaction. Only when they are filled can the worker attain true job satisfaction.


Level #5 Prove myself to myself
Level #4 Prove myself to others
Level #3 Desire to be a member of the team
Level #2 Concern for future security
Level #1 Concern for present well-being
Self
Ego-status
Belonging
Safety
Basic
Motivator Factors "Plus Territory"
Hygiene Factors "Minus Territory"

	Hygiene	Motivators
Absent	Dissatisfaction	No satisfaction
Present	No dissatisfaction	Satisfaction

FIGURE 1.4.8 Levels of needs.

Level #1: Basic Self (Creature Comfort). Concern for one's present well-being, comfort, strain avoidance, pleasant working conditions. Needs are filled by

Wage increases
Better working conditions
More vacation, longer breaks

Ineffective: motivators unrelated to work itself.

Level #2: Self-Security. Concern for one's future well-being, security, predictability. Needs are filled by

Secure job, fringe benefits
Health insurance, workman's compensation
Retirement income

Ineffective: motivators stem from standardized, conforming job performance with little chance for innovation or flexibility.

Level #3: Relationships with Others (Belonging and Affiliation). Concern with belonging and being an accepted member of the team or group. Needs are filled by

Company picnics and outings, organized sports programs
Extracurricular meetings regardless of content
Committee memberships

Typically ineffective: although at times may lead to employee satisfaction and loyalty, may cause lack of performance by diverting employees' attention from work to social relationships.

Level #4: Recognition (Ego-Status). Concern with achieving special status, chances to show competence. Needs are filled by

Special merit awards and recognition
Articles in company papers
Recognized by company, suppliers, customers as a key contributor

Effective: because these actions are motivators that are related to job itself for satisfaction.

Level #5: Ultimate Self (Actualization and Self-Expression). Concern with testing ultimate potential, chances to be creative. Needs are filled by

Job designs, special assignments
Opportunities for experimentation
Autonomy in decision making and use of resources

Most Effective: because employee is true partner in meeting both individual and company goals.

The following ideas are ways to use motivation skills and tactics on the job:

- Look for ways to both motivate and delegate more by expanding the job descriptions of your team members/subordinates.
- Use stretch goals to motivate for excellence and ultimate employee satisfaction.
- Train your team on the processes for problem solving, decision making, planning, and concerns analysis. Next identify a champion (who is motivated by the assignment) for each to institutionalize the process into your organization.
- Motivate your team by asking them how their job descriptions could be either reduced or expanded to make their assignments more meaningful (provided these new tasks are value added and in line with your company's goals and objectives).
- Ask each employee or team member for a 1- to 3-year career development plan and how you can provide the resources to help motivate them in their development.
- Motivate employees by remembering to thank them for their accomplishments.
- Determine if the Basic Self and Self-Security needs of your team are being met before asking them to set self-attainment (stretch) objectives.
- Assess your team's motivational attitudes, especially when working with a new team.
- Meet individually with your team to see how each of their job descriptions or project tasks could be expanded or changed to better mesh with their personal goals and company goals.
- Decide how you might change the scope of your job to make it more self-motivating and contribute more value-added content.

Management Style Skills

Assumptions about what motivates us is at the core of any theory of the management of people. Behind every managerial action are assumptions about human nature and behavior. The research work of Douglas McGregor [6] has led to insights into how we feel about human nature and behavior. He defined two descriptions of our beliefs and how these beliefs tend to guide our management style. An understanding of the theories of motivation shows that we all have wants and needs. As soon as one of our needs is satisfied, another appears in its place. This process is unending and we continuously put forth effort (we work) to satisfy our needs. However, a satisfied need is not a motivator of behavior. This fact is often unrecognized by one style of management (which is described by McGregor as Theory X) and has led to management policies and decisions that are ineffective motivators.

The common theme of the lower-level (basic and safety) needs is that we have to leave work to enjoy the rewards we are given to satisfy these needs. Wages, overtime pay, vacations, health and medical benefits, and profit sharing are examples. It is for this reason that many workers perceive work as a form of punishment. Satisfaction is gained only by being away from the job.

McGregor defined two theories that describe the extremes of management behavior. These are called Theory X and Theory Y. Both are based on beliefs about motivation and the resulting human behavior. The Theory X type manager has a traditional autocratic view about human nature and behavior. This type of manager believes that

- The average person has an inherent dislike of work and will avoid it if possible.
- The average worker prefers being directed, wishes to avoid responsibility, and has relatively little ambition.
- Most people must be forced, controlled, directed, and even threatened with punishment to get results in line with the company's objectives.
- Workers are motivated by rewards that appeal to their basic (lower-level) needs for security and safety and financial security.

The Theory Y type manager has a team-player view about human nature and behavior. This type of manager believes that

- The expenditure of physical and mental effort in work is as natural as play or rest. The average person does not inherently dislike work.
- External control or threat of punishment is not the only means to attain objectives. Workers will exercise self-direction and self-control to meet the objectives to which they are committed.
- Commitment to objectives is a function of the rewards given.
- We learn to not only accept but seek responsibility.
- The intellectual potentialities of the average worker are only partially used.

The single most important assumption of Theory Y is that worker contribution in an organization is not limited by human nature but by management's inability to discover how to realize the potential of its workforce.

Regarding Company Performance:

Theory X states poor company performance is due to the nature of the workers.

Theory Y states poor performance lies in management's methods of organization and control.

Regarding Worker Performance:

Theory X states that if workers are lazy, indifferent, unwilling to take responsibility, uncreative, and uncooperative, it is their nature to be that way.

Theory Y states these conditions are effects (not causes) resulting from poor managerial methods. This philosophy does not imply permissiveness or soft management. It does require flexibility in the use of authority and holds that autocratic style is not appropriate at all times in the manner of Theory X. This style is an invitation to innovation because it encourages the use of good interpersonal skills.

The Theory X and Theory Y management styles, along with three other common styles, are best visualized on the management grid as shown in Fig. 1.4.9. There are self-assessment tests (e.g., that of Teleometrics International [7]) available that can give you insight into your pre-

THE INDUSTRIAL ENGINEER AS A MANAGER

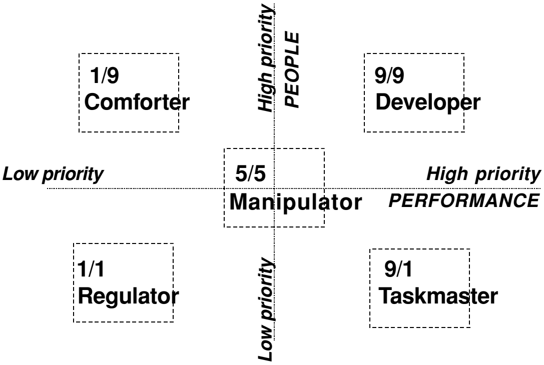

High priority
PEOPLE
1/9
Comforter
9/9
Developer
Low priority
5/5
Manipulator
High priority
PERFORMANCE
1/1
Regulator
Low priority
9/1
Taskmaster

FIGURE 1.4.9 The management grid.

dominate style and back-up styles. We first must learn the characteristics of each style, then selectively choose useful tactics from each style for a given on-the-job situation.

The 1/9 Comforter Style

- Focuses on people and their relationships
- Takes on a role as protector of people
- Little focus on production needs
- Believes people are fragile
- Sets low or few goals
- Fails to gain long-term satisfaction for the team
- Smoothes over conflicts without resolving them
- Believes people and work are in conflict
- Keeps things as they are
- Well liked but doesn't last long

The 1/1 Regulator Style

- Stays out of trouble
- Avoids risk
- Meets only minimum goals
- May be marking time until retirement
- Resigned to the "system"
- Often company straitjacket policies a cause
- Avoids conflict by not being involved
- Does busywork that is not value-added
- No expectation of personal satisfaction on the job

The 5/5 Manipulator Style

- A compromise style.
- Doesn't delegate.
- Manages everyone differently.

- Gives a little to get a little.
- Lack of consistency in behaviors.
- Team gets mixed signals.
- Unpredictable.
- Manipulative to gain stability.

The 9/1 Taskmaster Style

- Theory X philosophy.
- Wants results with a focus on short term.
- People don't count so they don't need to understand.
- Adheres to chain of command.
- Primary concern is output.
- People and work are in conflict.
- Treats people like any other tool in the workplace.
- Expects his/her commands to be followed without question.
- Autocratic style.
- People and work are in conflict.
- Overemphasis on metrics and procedures.

The 9/9 Developer Style

- Theory Y philosophy.
- People and work are interdependent.
- Knows conflict will exist and faces it head-on.
- Shares information.
- Believes people have an innate need to work.
- Work is healthy.
- Involves team in decision making.
- Shares ownership of successes.
- Believes most people are competent and responsible.
- Creates feeling of self-worth.
- Seeks opinions and gives feedback.

In summary, effective managers are aware of their position on the management grid. For most situations, they work diligently to deploy a 9/9 style. At the same time, they recognize that some situations will require an alternative style. They consciously choose an alternative style to use tactically to get results. In addition to understanding and using management style tactics, experience shows [2] that the effective manager consistently demonstrates five habits:

Habit #1: Time Management. Knows where his/her time goes. Tracks use of time and what activities are value-added versus non-value-added.

Habit #2: Process Focus. Focuses on the process by which (how) the work is done and the results of the process.

Habit #3: Team Strengths. Builds on his/her team's strengths rather than weaknesses. Identifies strengths of each player and emphasizes these rather than the weaknesses.

THE INDUSTRIAL ENGINEER AS A MANAGER

Habit #4: Effective Decision Making. Makes effective decisions, which first requires an understanding of the situation (problem) and the root cause(s) so that the decision effectively resolves the issue.

Habit #5. Delegation. Sets clearly defined priorities and knows how to delegate effectively.

The ability to delegate effectively is a decision making issue we face on a day-to-day basis. Delegation is made difficult for many reasons:

- I can do it better and quicker myself.
- It takes too long to explain.
- I can't give away important tasks.
- There's no one I can trust.
- No one is qualified to take on the task.
- It takes too much effort to follow up.
- There's no time to delegate on a rush job.
- I never get back what I want.
- Others don't like being asked to do my work.
- I'll lose control.
- I won't know what's going on.
- I won't be able to answer my boss's questions.

Some tips for helping to delegate effectively include the following:

- Set up a standard procedure for delegating (develop a routine that says who does what when).
- Train the designee in what you expect (the quality level, response time, etc.).
- Practice effective feedback methods (learn how to quickly assess the status of a job by asking the right process questions to get content data).
- Be willing to take a risk but minimize it by closing the feedback loop to assure the assignment is on track.
- Identify those members of your team who are best at taking on delegation.
- Compliment when the job is well done; provide constructive feedback when it isn't.
- Assess your workload to determine what routine tasks can be delegated so that you have adequate time for the emergency tasks.
- Make sure the assignment is clearly defined and well understood.
- Look for those standard, repetitive tasks that take up your time.
- Gradually increase the amount you delegate; don't make a step change.
- Prioritize your workload and start with those tasks that won't kill you if not done the way you could do them.
- Test the water (some are better than others at taking on delegation tasks).
- Motivate your designee by explaining why the task is important and needs to be done and why you've chosen the designee.
- Select a designee that makes sense, not just for you, but in that the task also benefits the designee. (A critical issue! Is the task value-added? If it is not, or if it is perceived to be non-value-added, then you need to question why it should be done in the first place. If you still decide it must be done, then have some good reasons why it is important.)
- Use delegation as part of the development plan for subordinates.

The following ideas are ways to use management style skills and tactics on the job.

- Ask every day, "What can I do to assist my team?"
- Expand your list of ideas for assisting your team by adding a new idea every day.
- Before giving an assignment to my team, first assess what management style is appropriate. Does it warrant a 9/1 authoritarian style or a 9/9 team style?
- Set aside a certain amount of time to periodically mentor/coach/train your team on effective management styles and tactics.
- Assess your team to determine their attitudes about management style. Are there any Theory X (workers inherently dislike work) attitudes? If so, how does this affect the functioning of your team?
- Assess what your team perceives to be your management style. Do they consider it effective?
- Review each of the five management grid positions and the characteristics of each style to determine if you are using ineffective tactics from any of the styles not within the 9/9 style.
- Define a plan for delegating effectively using the list of tips for effective delegating.
- Assess your difficulties in delegating.
- Determine how well you follow the five effective management style habits. Which ones do you need to emphasize more?
- If you work with someone who has an ineffective management style (uses techniques that are not typical of a 9/9 team management style), help them to understand the concept of the management grid to improve their management style.
- Review the five management grid styles and determine under what types of situations you would intentionally use each of the styles. Consciously develop a set of management style tactics using each of the styles when appropriate.
- One of the five effective management style habits is to build on the team's strengths. Review your team's strengths and reassess how you can more effectively use them.
- One of the five effective management style habits is to know where your time goes and what activities are value-added versus non-value-added. Review your use of time and audit whether the tasks you perform are value-added or non-value-added. Do the same with your team. Eliminate or at least minimize the non-value-added tasks.

Interpersonal/Communication Skills

Studies of multinational corporations have shown that often up to 75 percent of managers sampled from companies in Japan, the United Kingdom, and the United States cited communication breakdown as the single greatest barrier to corporate excellence. Unfortunately, "communication breakdown" has become a convenient and overused catch-all for explaining corporate ills. The fact is that communication problems are not the cause, but the symptoms, of more basic issues within a company. When management is effective and working relationships are sound, problems of communication tend not to occur. It is only when a company's management team is not working together effectively that "communication breakdown" surfaces. Employees feel and express concern about lack of direction, distrust, resentment, and insecurity. These typify all the negative attitudes that managers must deal with effectively to get results.

The single most determinant factor contributing to how well a company's management team works together is its interpersonal style. The concept of interpersonal style is not an easy one to quantify. Fortunately, there is one technique that managers can use to judge and improve the quality of their interpersonal style in dealing with others. This technique is the Johari Window, which is based on the studies of Joseph Luft and Harry Ingham [8] and is depicted in Fig. 1.4.10. The Johari Window is an information processing model that relates

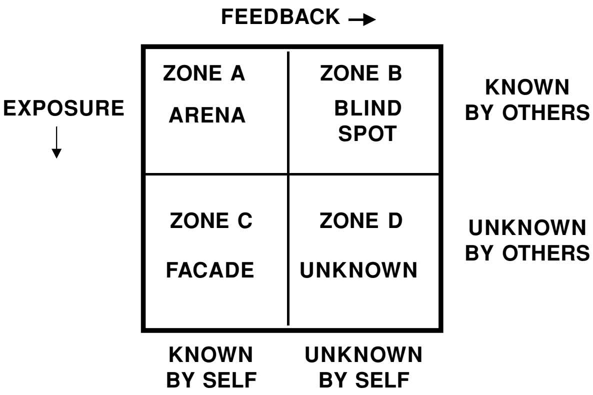


FIGURE 1.4.10 The Johari Window.

interpersonal style and individual effectiveness in communicating information (both the giving and receiving of data) to others. The value of the Johari Window concept is that it can provide insight into the consequences of the lack of proper communication behavior. The Johari Window model consists of four squares or zones of knowledge.

Zone A, the Arena, defines knowledge or information known both by yourself and others. The Arena is the territory of everyday working space, where we and our team gain results by working with shared knowledge. The larger this body of knowledge, the more effective the team.

Zone B, the Blind Spot, defines that area of information that is known by others but not ourselves. This is the area of hidden, unperceived information. The data that reside in Zone B become an interpersonal handicap for the individual manager who cannot understand the behaviors, decisions, or potentials for others if he or she doesn't have the data upon which these are based. One obvious way to reduce the relative size of this zone is to solicit data, to question, and to be receptive to feedback.

Zone C, the Facade or protective front, is defined as that area of information known by oneself but not by others. It is the data one chooses not to share and which serve as a defensive mechanism. Each of us establishes interpersonal relationships with some degree of defensiveness, where we intentionally do not share all data with others. This facade may at times be necessary, but can often inhibit the communication of important data to others and interfere with their abilities to get the job done. Have your ever worked for a manager who kept his cards so close to his vest that you had to guess at objectives, priorities, or even the rules?

Zone D is the area of information unknown by both yourself and others. This is the area of hidden potentials known as the data base of creativity. The manager who can move his or her interpersonal relationships concurrently into Zones B and C attains a synergism from both zones that automatically moves both members of the relationship into the database of creativity hidden in Zone D. The partners of the relationship together begin to explore new ideas, concepts, and opportunities because of their mutual sharing of what was once mutually exclusive information. The manager who has the interpersonal style of both exposure use (to share his personal knowledge) and feedback solicitation (to question and encourage feedback) not only will excel in performance but will also be seen as the astute leader who has effectively solved the communications breakdown problem.

The size and shape of your Arena is reflective of your interpersonal style. Your interpersonal style in turn demonstrates the behaviors you exhibit with your subordinates, your peers, and your supervisors. The ideal Arena is a large, square knowledge and communication window. However, often the work environment, the company culture, and the people we work with will impact the shape of our Arena. As you review the following four interpersonal styles, determine if any of them are characteristic of your style. Explore reasons why your work environment and the people you deal with may cause you to have a less than desirable Arena. If the Arena or size of the window of communication and subsequent knowledge transfer is equally small (less than 80 percent) along both axes, then it may signal the use of the following behaviors:

- Minimal use of both exposure and feedback processes.
- Impersonal approach to interpersonal relationships.
- Unknown region dominates.
- Results in unrealized potential and untapped creativity.
- Withdrawal and aversion to risk-taking.
- Safety-seeking a prime source of motivation.
- Behavior is detached, mechanical, and uncommunicative.
- Often found in bureaucratic, highly structured organizations.
- Use of Small Arena behaviors on a large scale in a company reveals a poor work environment and may signal an unhealthy organization.
- Organizational creativity and company growth limited and at risk.
- Subordinates view you as aloof, indifferent, and often indecisive.

If the Arena is larger in the feedback dimension than in the exposure dimension, then you should be alert to these behaviors:

- Minimal use of exposure (giving information) but a need for relationships by soliciting feedback.
- Not giving information may be a sign of basic mistrust of yourself and others.
- Taker not giver behavior.
- Behavior has facade of concern but true motivation is to strengthen one's own position.
- Use of the style in organizations leads to lack of trust and promotion of an image of confidence and resultant power plays for organizational and functional control.
- A "what's mine is mine and what's yours is mine" mentality is demotivating to subordinates.

If the Arena is larger in the exposure dimension than in the feedback dimension (large Blind Spot), then you should be alert to these behaviors:

- Overuse of exposure with little or no interest in asking for feedback.
- Reflects high ego and/or distrust of others' competence.
- Person is unaware of his impact or of the validity of others' contributions.
- Subordinates feel disenfranchised and that manager has little use for their contributions or concern for their feelings.
- Style triggers feelings of hostility, insecurity, and resentment.
- If, during a conversation, you are more concerned about what you are going to say than about listening to what is said, you may be the type.
- Many organizations force this type of performance by requiring the manager to demonstrate broad competencies.
- Relationships will be dominated by Blind Spots and these managers will always be surprised when feedback is forced on them.

Managers who have equally large exposure and feedback dimensions deploy effective interpersonal skills and behaviors as evidenced by the following:

- Exposure and feedback processes are used and balanced.
- Behavior is one of candor and openness combined with sensitivity to others' needs.
- The Arena becomes the dominant feature of the relationship.
- This style asks not only what the subordinate has done but what can be done to help the subordinate perform better.
- Initial reaction to use of this style may be defensive on the part of others who are not familiar with honest and trusting relationships.
- Continued use will promote reciprocal candor over time leading to trust.
- Healthy and creative work climates result from this style.
- For optimal results, the data exchanged should be pertinent to work issues.
- Trust is slowly built and this style of manager must be prepared to be patient.
- The challenge for this style manager is to decide when and what information should be sought and given and to include this task in his or her day-to-day decision making.
- The organization dominated by this style of manager will be successful because of their supportive behaviors and focus on the sharing of information and knowledge. These are the managers of "learning organizations."

The following ideas are ways to use interpersonal/communication skills on the job:

- Use the Johari Window concept to open up the Arena zone into the creative/innovative zone in brainstorming sessions by intentionally relating information known to you but not by others.
- Use the Johari Window concept to better understand your team's communication style and, if you need to open your window, to improve your effectiveness.
- Set a personal goal to open your Arena for both feedback and exposure transfer of information.
- Review the characteristics of those interpersonal styles that are not ideal to determine if you use any of these ineffective communication techniques and, if so, how you should change.
- Review the characteristics of the large Arena (ideal) interpersonal style to determine which techniques you should emphasize to open your Arena.
- If you work with someone who has poor interpersonal skills (a small Arena), explain the concept of the Johari Window and help them to understand the results so as to increase the size of their Arena.
- Ask your team to give you feedback on how effective your communication skills are in dealing with them. Ask for them to assess how well you both give information and solicit feedback from them.

SUMMARY OF PERFORMANCE CHARACTERISTICS

As organizations reconfigure to optimize performance through wider use of multifunctional teams, you have to recognize your changing role. You must now demonstrate excellent technical skills, managerial skills, leadership skills, and finally process skills as owner of the processes for your department or team. An entirely new set of measurement criteria has evolved by which you will be evaluated. No longer will you only be measured on your results against your company's annual operating plan objectives and strategic plan objectives. You most likely also will be measured against several of the following performance characteristics. Review this list and see if there are some characteristics you need to emphasize.

Analytical Abilities: Analyzes issues systematically, using sound, logical judgment and value-added processes:

- Gathers and processes information logically to reach a clear understanding of concerns
- Investigates and identifies root causes of problems
- Evaluates potential solutions for short- and long-term costs and benefits
- Uses both logic and intuition to reach appropriate conclusions

Coaching/Teaching/Developing Others: Fosters a challenging environment that motivates and encourages employees to perform at their highest possible level:

- Sets a climate that supports learning and development
- Accurately assesses strengths and development needs of employees
- Works to create and implement development plans to improve employees' skills and performance
- Provides accurate, frequent, and timely motivating performance feedback
- Offers specific work-related advice, suggestions, and alternatives

Tolerance for Ambiguity: Works effectively in unsure circumstances and can effectively balance personal and work-related activities:

- Deals effectively with uncertainty, ambiguity, and lack of direction
- Demonstrates appropriate level of patience when trying to get things done
- Displays self-confidence when working under confused or uncertain conditions
- Performs well under pressure and time constraints

Communication: Demonstrates open and effective communication skills with subordinates, peers, and superiors:

- Listens to others, respects their differences and opinions
- Keeps people informed and channels of communication open
- Writes in a clear and concise manner
- Makes effective formal presentations
- Seeks feedback from and provides information to others as needed

Interpersonal Skills: Works and demonstrates good teaming and interactive skills with subordinates, peers, and superiors:

- Establishes effective working relationships with others
- Is receptive to ideas and suggestions from others
- Displays sensitivity for the needs and concerns of others
- Resolves conflict in a win-win way

Initiative/Resourcefulness: Works for continuous improvement by looking for new and innovative resolutions of concerns; takes action in initiating an idea or project and then follows through to its completion:

- Takes initiative in raising issues and completing work
- Finds innovative ways to get results
- Continually refines and improves the way work is done
- Persists even in face of difficulties and barriers
- Works well without supervision

Integration/Connectivity: Able to grasp complexities and to perceive relationships among problems or concerns; able to consider a broad range of internal and external factors when solving problems, making decisions, and prioritizing concerns:

- Takes the big picture into consideration during assignments
- Sees connection between various work elements and integrates elements
- Brings together different perspectives and approaches, blending and building for best results

Juggling Competing Priorities: Able to effectively complete large volumes of quality work and to be increasingly responsive to get the job done by managing time effectively:

- Establishes realistic, measurable, and clearly defined goals
- Prioritizes work assignments to meet deadlines
- Handles several tasks and responsibilities simultaneously
- Creates contingency plans and alternative approaches

Results Oriented: Persistently works towards goals and objectives and gets results:

- Sets high standards for self and others
- Delivers on commitments
- Follows up to make sure concerns are resolved and assignments completed
- Identifies and attends to important details

Speed and Effectiveness of Decision Making: Able to take quick and appropriate actions when faced with limited time and information:

- Makes the right decisions; exhibits sound judgment
- Takes a stand on issues and decisions made
- Displays an aptitude for taking action and calculated risks
- Measures results and takes corrective action when needed

Empowerment: Helps employees to perform better and in a more self-directed way by helping the employee to feel an increased sense of control over his or her work, decisions, and environment:

- Encourages high degree of involvement, responsibility, and commitment
- Supports appropriate levels of risk-taking
- Pushes decision making and problem solving down to lowest appropriate levels
- Allows staff to use their best judgment and discretion to determine how to accomplish work results
- Provides staff members with enough information to do their jobs

General Business Knowledge and Acumen: Understands how the organization operates and its place within the larger context of industry, the marketplace, and the competition, and knows the role of different functions necessary for the success of the organization:

- Understands internal/external environments that impact the company
- Displays a good understanding of company's mission, goals, strategies
- Demonstrates knowledge of technical/functional aspects of work
- Displays a strong customer focus, awareness, and sensitivity

Influence/Impact: Knows how to gain cooperation, support, and commitment from others both inside and outside the organization:

- Effectively persuades others to adopt/accept ideas
- Makes his or her points in a timely and astute manner
- Gains cooperation, support, and commitment from others without relying on position or formal authority
- Recognizes and responds appropriately to political and practical realities

Teamwork: Builds and facilitates multifunctional teamwork relationships:

- Recognizes the need for teamwork and cross-organization teams
- Works effectively with others, combining personal effort while drawing on the contribution of team members
- Builds common understanding and shared agreement among team members
- Shares staff and resources with others when appropriate
- Works with peers to head off potential conflict of goals, duplication of effort, or waste of resources
- Demonstrates both effective team leadership and membership skills

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CHAPTER 1.5

FUNDAMENTALS OF INDUSTRIAL ENGINEERING

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This chapter covers the basic industrial engineering tools, methods, and procedures and specifies their appropriate application areas for improvements and problem solving. The topics will be explained from a layman's perspective with reference to other chapters in this handbook.

BACKGROUND

The theoretical basis of industrial engineering is a science of operations. To successfully use this science in most applications one must simultaneously consider at least three criteria: (1) quality, (2) timeliness, and (3) cost—whether it be a blood bank in Missouri, the U.S. Naval Shipyard in Hawaii, or a knitted socks factory in North Carolina. The principles of industrial engineering are not only universally applicable across industries, but across all operations in government, commerce, services, or industry.

Almost always, the goal of industrial engineering is to ensure that goods and services are being produced or provided at the right quality at the right time at the right cost. From a business perspective the practice of industrial engineering must culminate in successful application. This requirement typically dictates that a practicing industrial engineer effectively use "soft" as well as "hard" science. In the final analysis, the industrial engineer's job is to make both new and existing operations perform well.

The preponderance of traditional industrial engineering techniques deal with physical entities (e.g., equipment, buildings, tools) as well as informational entities (e.g., time, space) for an operation, employing what can be thought of as hard science. However, management-related factors in the workplace that determine the motivation level of an employee to perform his or her assigned duties well, or actively participate in operational improvement over time, represent the soft science of industrial engineering. In recent years, there has been a growing awareness of the importance of this soft science component of industrial engineering. Not only must the motivation of individual workers be attained through effective management efforts, but the motivation of work groups as well. Individual workers rarely work alone; they typically respond to a social need to fit in as a member of a work group.

In most organizations, as a matter of modern management practice, management will create a vision, perform strategic planning and goal setting, and establish performance measurement system development roles (see Chaps. 2.1 and 2.4); the products of these efforts will be available throughout the organization. These documents guide all operational activities. In those instances when industrial engineering is attempting to perform its role and has determined that there is no clearly articulated or available vision, plan, goals, or performance measurement system in place, it is important that these prerequisite efforts be encouraged to take place before, or at least parallel with, anticipated industrial engineering activities. Nominal group technique [1, 283–284] improvement opportunity sessions of personnel throughout most components and levels of an organization can help build a consensus-driven and guiding improvement plan for everyone in the organization to embrace as their own, or at least accept as one in which they participated in its development. Such an effort is critical because there seems to be an important fundamental psychological truth that involvement leads to commitment, which leads to performance.

OPERATIONS ANALYSIS AND DESIGN

Methods Engineering

A production system is essentially the sum of its individual operations. Therefore, it follows that if one wants a production system to be efficient then its individual operations must be efficient. Working from a bottom-up micro perspective, one approach is to simply review all individual operations to make them the best they can be (see Chap. 4.1). One reason such an approach offers considerable opportunity for improvement today is that it has been often overlooked while the search for the single "silver bullet" macro solution occurs in the front office or the boardroom. In many firms today individual workstation cycle times can be reduced by one-third to one-half of their present average cycle times by implementing a short list of modest improvements in these workstations.

Charting techniques have proven to be useful for analyzing operations. (Refer to Chap. 17.1 for a thorough discussion of the charts mentioned in the following paragraphs.) The operation process chart allows the analyst to visualize the sequence of operations for a product whether it be a bicycle or an insurance form. The circles on such a form typically represent operations that are considered to be value-added activities in the process flow. From the customers' perspective, what they want is the completed (i.e., assembled) item; therefore, only operations that add directly to the physical completion of the product are considered value-added. Inspection does not add to the completion of the product and is considered a non-value-added activity. Many production organizations now practice simultaneous inspection by letting the next operator in a process inspect the previous operator's work to minimize the need for inspectors.

When the analyst understands this sequence of operations, his or her attention often turns next to analyzing a segment of the overall process in more detail, employing a flow process chart. The interest is more focused now on such process activities as storage, transportation (i.e., material handling), and delay. These activities do not add directly to product completion and, therefore, are typically considered non-value-added activities on the flow process chart.

A multiple activity chart is any chart that displays more than one resource using a timescale to determine the best combination and timing of multiple resource activities in identifying a shortest cycle time for the operation. Such commonly used charts as a human-machine chart, "left-hand, right-hand" chart, crew chart, and gang chart involve multiple resources. An obvious example of a multiple activity chart would be a chart displaying the time-scaled activities of various resources attempting to get on a fire truck (e.g., driver, dalmatian dog, firefighter, the call taker, etc.) to permit the fire truck to leave the fire station in minimum time. Multiple activity charts are one of the simplest and yet one of the most useful techniques in industrial engineering for improving operations involving multiple resources.

Most products have traditionally been designed employing a sequence of organizational entities—for example, marketing, research and development, product design, process design, tool design, methods engineering, plant layout, and material handling. Such a sequential approach to product design requires each organization to operate without the benefit of inputs from organizational segments that traditionally follow their activity. When these various entities are engaged in product design as a design team, however, the overall product development time is often reduced considerably and the design is typically much improved from the perspective of the final user as well as in the manufacture of the product (see Chap. 13.1). By providing early-stage inputs, a producibility engineer, a manufacturing engineer, a materials engineer, a tool engineer, a methods engineer, a quality engineer, or an industrial engineer can request design adjustments that permit more timely and more cost-effective operations at higher quality levels (Chap. 14.2). As a member of a design team, producibility and manufacturing engineers today often employ design for manufacture (DFM), design for assembly (DFA), or manufacturability [2] concepts (Chap. 13.2) to provide more cost-effective approaches to the manufacturing process. Such up-front design adjustments typically produce tremendous cost savings and product quality improvements over the life cycle of the product.

The culmination of a methods engineering effort is the determination of a documented best method for an operation that is then used as the standard method. Workers are required to employ the standard method in performing the operation. For example, when a patient arrives for an x-ray, the process of entering that person into and completing the x-ray process should be predetermined to best serve all patients, required procedures, equipment and facilities, and the x-ray department staff.

Work Measurement

Fundamental to the traditional practice of industrial engineering has been the use of "labor reporting" rather than "direct supervision" as the preferred approach for attaining cost-effective labor operations (Chap. 5.7). Rather than watching an employee and telling them whether they are working hard enough (direct supervision), a supervisor employing labor reporting uses the standard time for the operation to produce an estimate of the number of items that should be produced by an employee in a given time period, such as a week or a month. This estimate assumes that the worker had the opportunity to be productive during the time period (e.g., there was no major power outage during the period in question). At the conclusion of a time period, the supervisor compares the estimate of production with the actual production accomplished as a basis for evaluating the relative productive accomplishment of the employee.

Use of the labor reporting approach to worker productivity evaluation required the development of a standardized procedure for determining the standard time for an operation. The most direct method developed to date—time study—uses a stopwatch to measure the elapsed time for an employee performing an operation (Chap. 17.2). While the worker is being timed, the time study analyst must also evaluate the relative pace of the employee performing the task by estimating a performance rating factor. When completing the time study form the analyst multiplies the average observed time for each element of the operation by the performance rating factor for each element and sums these products to arrive at the expected rate of performance at a normal pace. This time value is called the *normal time* for the operation, and is the expected time for making one unit of production. Workers are not expected to work every minute of their shift, however, so nonwork time is added to the normal time to arrive at the standard time for the operation, which includes both the expected productive time as well as the allowed nonproductive time for producing one unit of production.

The expected nonproductive time included in a time standard is referred to as an *allowance* (Chap. 5.5). There are typically three components of the total allowance provided, commonly referred to as P F & D, which stand for *personal, fatigue,* and unavoidable *delay.* The personal allowance is time provided to the employee to rest and to attend to personal needs, such as going to the bathroom. Morning and afternoon breaks, for example, make up a part of the personal allowance. The fatigue allowance is the recovery time needed by an employee performing a fatiguing operation, such as shoveling coal into a boiler. After performing the work for a while the employee needs to rest to recover from the fatigue before performing the shoveling task again. It essentially involves estimating an appropriate *duty cycle* (i.e., analogous to "on" and "off" times for a heater controlled by a thermostat) for the employee, for work and rest. The unavoidable delay allowance factor is typically determined by measuring the percent of time an employee is prevented from being productive by the production system in which he or she works. Equipment downtimes, supervisor conversations, unavailability of tools or materials are all typical unavoidable delay causes. The three allowance factor percentages (i.e., P F & D) are added together and the sum (e.g., 8 percent) is used to add additional time to the normal time (work time) to determine the standard time (work and nonwork time) for the operation. The total time in minutes an employee works in a given work period can be divided by the standard time to determine how many production units he or she should have produced in that period (see Chap. 5.4).

Predetermined time systems have been developed over the years, such as methods time measurement (MTM) and Maynard Operation Sequence Technique (MOST), which provide standard times for categorized human motions (see Chap. 17.4). By specifying a sequence of human motions that represent a task employing such a system, an estimate of the standard time for performance can be determined.

More macro work measurement techniques, such as work sampling, are used to acquire macrolevel information about operations. Work sampling (Chap. 17.3) involves making a series of random observations of activity. The results of such a study provide estimates of the percent of time devoted to numerous categories of work and nonwork for a specific type of job function, such as mechanical maintenance of a generating unit at a power plant.

By using standard times discussed earlier as a basis for evaluating productive performance, numerous work incentive systems (Chaps. 7.1 and 7.4) were developed in the past to reward employees for their work performance beyond the expected standard performance. Because these systems compensate employees relative to their performance, they have been a primary source of labor grievances (Chap. 7.5) concerning the details associated with incentive systems development and maintenance. Although useful for gaining higher levels of worker performance, such systems have tended to separate employees from their management.

Ergonomics

Most production and service processes involve a combination of equipment and human resources. Equipment resources can be modified to suit the needs of the process whereas the only opportunity for changing human resources in a process is through selection (e.g., perhaps no former NBA basketball player could fly a military fighter jet because he would likely exceed the height limitations).

Equipment typically proves superior to humans for tasks involving controlled, and very high or very low, levels of force, activities performed in hostile environments, or rapid and complex calculation. The most cost competitive capabilities of humans are their sensory abilities (i.e., sight, hearing, smell, feel, etc.) and their ability to make judgments in complex situations. Their ability to perform well however can be severely limited by environmental factors, both physical and psychological. Therefore, over the years two primary roles for machines and humans have evolved. Machines do the work: Humans in protected environments monitor and maintain machines. There are four primary subcategories of ergonomics concerned with the ability of humans to perform work: (1) skeletal/muscular, (2) sensory, (3) environmental, and (4) mental. See Chaps. 6.2 and 6.4 for further discussion.

An excellent brochure recommended to all who wish to know more about ergonomics is "Sprains and Strains: A Worker's Guide to Job Design," [3] which is specifically concerned with ergonomics problems in the automotive industry, and is a bargain at $2 a copy. Much of what is described, however, exists in most industries. The brochure is divided into three key areas of ergonomics concern in most industries: (1) the back, (2) the hands, and (3) the arms.

Specific maladies affecting the hands such as carpal tunnel syndrome, tendonitis, and white finger are discussed.

Facilities Planning and Design

A question that must be resolved by any organization is where to locate what facilities of what size and arrangement? The location question is typically hierarchical in that one must determine

1. Where should facilities be located geographically—southern Alabama?
2. On which specific site in southern Alabama?
3. How should each facility component (plant, water tower, office, warehouse) be located on the site?
4. How should space groupings (e.g., departments) be located within buildings and in relation to one another?
5. How should equipment be arranged within a designated production space?

The goal is to place properly sized and arranged facilities at locations that will result in a minimum total cost of delivered products to the organization's customers (e.g., distribution centers) of such facilities. See Chap. 8.1 for further discussion on location.

A key step in the layout of any production facility is the determination of how best to locate major spaces one to another within a building envelope—commonly referred to as a *block* layout (Chap. 8.2). Fortunately for all who must deal with this problem, Richard Muther [4] years ago developed a technique called the *activity relationship chart,* which effectively addresses this problem. The activity relationship chart [1, 93–97] requires the analyst to list a proximity-level (i.e., need for closeness) estimate for all space pairs. For example, the proximity-level relationship between receiving and raw materials warehouse would typically be "E" for *especially important,* because almost all raw material entering the plant through receiving will proceed to the raw material warehouse. After all space pair relationships have been estimated, a block layout is developed by taking the space with the largest number of high-level relationships and locating it first in the layout as a nucleus space (e.g., production), and then successively adding the remaining highest level relationships space, until all spaces have been located in the layout. Next, all space shapes are adjusted so that they will fit into a reasonably shaped facility envelope (e.g., a rectangle). This technique typically prevents the misplacement of spaces in a block layout.

There is a relatively consistent process [1, 84] for developing a facility design. The first step in the process is to evaluate two product attributes: the product design, and the life cycle sales volume of the product (Chap. 3.5). The design of the product typically limits the selection of cost-effective manufacturing processes (e.g., a part designed as an extrusion allows fabricating the part from an extruded raw material). The second attribute—life cycle volume—allows one to consider higher levels of automation, or at least mechanization, if the total number of products to be produced is sufficient to justify the higher initial cost of such equipment. Once these issues are resolved, the choice of specific equipment to be employed at various steps in the process can be determined. With assumptions of unit processing times, yield rates, and desired output rates, one can next estimate the number of each process step equipment needed [1, 89, 92]. Once direct labor is determined to accommodate the processing equipment, indirect labor (e.g., stockroom clerk, maintenance person) requirements can be determined. All of these determinations, and others, are prerequisite in developing the plant layout.

Simulation

When the layout for any complex process is completed, often irrespective of how detailed an analysis was performed, one remaining question that can directly affect the success of the layout may need to be resolved. The question is, "How much material will accumulate at the numerous steps and junctures in the process?" This is a queuing question, and unfortunately, humans are intuitively poor estimators of queuing outcomes for dynamic systems. Computer simulation of a process can assure, if the process is properly modeled, that process accumulations and process outputs have been properly estimated and that an appropriately sized and arranged facility can then be designed to house the process. Not always, but in numerous instances, the cost of computer simulation is well justified.

Material Handling

Material handling is the core non-value-added activity in most processes. Of all the hundreds of principles of material handling that exist (Chap. 10.2), probably the most important is "The best material handling is no material handling." Material handling has traditionally had the connotation of the movement of materials between locations, for example between workstations. If one broadens the definition somewhat by referring to that type of handling as *interoperational handling,* a second type of material handling can be designated as *intraoperational handling:* the movement of materials within workstations. Years ago Ralph Barnes, incidentally granted the first Ph.D. in industrial engineering, detailed his Principles of Motion Economy [5, 222–301] for improving the efficiency of workstations. Review of these principles indicates that in many instances there are principles for minimizing intraoperational handling. As stated previously, the customer wishes to buy an accumulation of product transformations (e.g., joining and finishing operations, such as assembly, welding, bonding, and painting), which constitute a finished product for his or her use. The material handling a manufacturer encumbers in creating the final product is simply a non-value-added cost of doing business. To the extent that a manufacturer can limit material handling costs—both inter- and intraoperational—profit is increased. It behooves a manufacturer, therefore, to devise the means to accomplish the required transformations at minimum cost while minimizing all material handling costs.

When performing a material handling analysis it is important to know what the material handling requirements are in a process. A "from-to" chart specifies these relationships. The material handling system is then designed to accommodate these requirements.

OPERATIONS CONTROL

Production

The production control organization in a plant has the responsibility for scheduling and controlling the issuance of production orders to the manufacturing floor (Chap. 9.2). A computerized program called MRPII (Material Requirements Planning II) has often been used to support these tasks. The program considers the master schedule for finished products, and employing lead times for purchase and hierarchical fabrication and assembly operations, determines dates at which events must occur (e.g., placing a purchase order for raw material) to meet these product delivery dates. Such computerized efforts lead to extensive tracking of production material over time. When using traditional progressive departmental assembly methods, the amount of work in process (WIP) is often considerable.

Production control has also dealt with such issues as line balancing (Chap. 17.8). Line balancing algorithms or heuristics [1, 170–173] attempt to assign work elements to workstations to minimize the number of stations required to produce a product for a given cycle time for the line. The goal is to minimize the amount of direct labor allocated to the line to minimize overall labor costs.

Just-in-Time

In 1955, Taiichi Ohno, with the support of Toyoda Eiji, chairman of Toyota, initiated the *kanban* system, which stated as a guiding principle: "What you need, only in the quantity you need, when you need it . . . and inexpensively as you can" [6]. The Japanese word *kanban* refers to the label on the front of a container designating what is in the container. Later called just-in-time (JIT) (see Chap. 9.4) in the United States, it involved a "pull" discipline (Chap. 9.6) of issuing production orders in considerable contrast to the traditional "push" system that had been employed. MRPII programs effectively push material onto the production floor based on its lead time calculations irrespective of the immediate need on the manufacturing floor for that material. In contrast, the pull discipline of JIT requires that an empty container (i.e., a kanban) be passed back into the system as authorization to fabricate more parts or to make more assemblies. This discipline considerably reduces the amount of material in the process. What has been learned over time in producing under that discipline is that numerous impediments to successful production have to be dealt with to produce good product with such a limited amount of material available. Both quality and productivity improved considerably as the impediments to the limited material availability were resolved. It was no longer possible to hide bad methods, equipment, and tooling that produced bad parts in an excessive amount of in-process material.

One of the greatest impediments to operating with reduced work-in-process inventories is traditional economic order quantity (EOQ) thinking [1, 144–146]. A key determinant in the traditional economic production quantity (EPQ) calculation [1, pp. 156–158] is the setup time for a machine that produces more than one part. Setup times in the past received little attention and as a result have been excessive. They lead to high economic production quantities. Shigeo Shingo, a Toyota engineering manager, determined that setup times can be significantly reduced, often by an order of magnitude (i.e., one tenth) compared to their previous values, as demonstrated in his book [7]. Therefore, one of the keys to cost-effective production of small lot sizes in manufacturing is reducing setup time. Many organizations are making great strides today in reducing their setup times through long overdue engineering analysis (see Chaps. 4.4 and 4.5).

As mentioned previously, only operations on a flow process chart are considered value-added activity. The four remaining categories of activity—moves, inspection, storage, and delay—are all considered to be non-value-added activities. In considering the placement of machines in sequence to accommodate the progressive fabrication or assembly of a part or assembly—cellular manufacturing—it became apparent that such an arrangement of equipment can essentially minimize, if not eliminate, non-value-added activities in a line. Assume for the moment that a worker puts a product down on the right side of his or her bench and the next worker picks up the product on the left side of his or her bench, and this arrangement continues for a number of successive operators in the line. A flow process chart for this line will show a line-by-line sequence of value-added steps (i.e., operations) containing few, if any, lines for non-value-added activity (e.g., move, inspect, store, delay). The production line therefore represents high ratios of value-added activity. This explains why cellular manufacturing is so popular today (see Chaps. 8.4 and 8.6).

Machines were not grouped in manufacturing cells in the past because it often appeared to require more machines to operate in a cellular manufacturing arrangement. Assume for the moment that 8 step A machines can keep up with 10 step B machines that can supply the input requirement of 9 step C machines. Arranging the machines in 10 manufacturing cells containing 1 each of step A, B, and C machines would appear to require the purchase of 2 more step A machines and 1 more step C machine. If, however, manufacturing cells are more productive because each cell team has control of their total process (i.e., steps A, B, and C), 8 cells may well outproduce what the 3 progressive assembly departments (i.e., departments X, Y, and Z) produced before, in which case there are now 2 excess step B machines and 1 excess step C machine. Note also that the material handling requirements between machines employing the cellular manufacturing arrangement have been greatly minimized, if not eliminated. In running the cell, with cross-training so that employees can run more than one machine, it may be determined that 2 employees can run a manufacturing cell containing 3 machines whereas previously each machine required 1 employee to run. The potential for both productivity and quality improvements employing manufacturing cells has been clearly demonstrated for some organizations in recent years.

Cellular manufacturing has led some manufacturers to appreciate the value of moving to nonfixed allocation of line labor. Assume for the moment that there are 10 different machines successively employed in a manufacturing cell, and the sum of the labor requirement employing real, not integer, values is 7. By assigning 7 cross-trained workers to the manufacturing cell, the amount of production accomplishment can equal that of 10 workers with fixed assignments to the 10 machines. Each worker can work at a workstation until a predefined number of *kanban*-completed item positions at the workstation are filled—at which time the worker moves to another open position on the line. Each worker can work at their own pace. The less motivated or fatigued worker can work at a slower pace while the highly motivated or less fatigued worker can work at an increased pace and not be delayed by the slower worker. Such an approach eliminates the need for line balancing.

Inventory Control

Warehouses have been a long-standing tradition in manufacturing. Analysis of their contribution to value-added activity, however, demonstrates that they offer none. All warehouse activity simply adds to the cost of doing business. It is not surprising, therefore, that some arrangements have been made in industry that either minimize or eliminate them. Point-of-use storage places the raw material where it will be used by a machine in the process. If a local supplier two buildings away can deliver this material on a relatively continuous basis—for example, a pallet load a day—this material need not be housed in a non-value-added warehouse. One component manufacturer, a seat manufacturer for a motorcycle manufacturer, has a seat factory next to the motorcycle factory, and delivers the seats by forklift to the motorcycle production line as needed. The bread delivery person analogy explains the ideal arrangement. Most supermarkets have arrangements with a bakery such that their delivery person supplies bread to the bread aisle as needed to meet the requirements of supermarket customers. The supermarket management, in effect, has an ongoing relationship whereby the bakery plans and worries about supplying the line, and the store management concentrates on store issues other than bread. Such partnering relationships are becoming more typical today with suppliers having limited access to the manufacturer's computer for determining future requirements and the supplier simply responding to these supply requirements over time. Development of a local supplier base makes these arrangements easier to develop.

The primary role of inventory is to accommodate unequal flow rates. If customers do not buy products at a constant rate during the year, it is common practice to produce at a more level rate than the demand rate, warehousing the excess product produced during the lower buying period, and then supplying the excess demand in the higher demand period of the year from inventory. There is a cost associated with inventorying product, however. If one varies the capacity of the producing system to accommodate the variable demand by varying the labor assigned to the process, there may be no need to inventory product. Today organizations are finding unique ways to match supply with demand to eliminate the need for inventories by hiring temporary employees or part-time employees, such as college students, during peak periods.

Quality Control

Quality control as an organizational entity evolved from workers previously called *inspectors* who sorted good material from bad (see Chap. 13.4). Inspectors were typically disliked by

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production workers because they passed judgment on whether what was being produced was good enough. In time, the concept of identifying the cause of the bad product and eliminating the cause seemed a better approach than simply sorting good product from bad, and the term *quality control* was born.

Today quality function deployment (QFD) [8] presses this "understanding the cause" perspective even further. QFD efforts perform an objective evaluation of the specific product attributes, strengths, and weaknesses in comparison to competitive products so that the manufacturer can better understand customers' willingness or unwillingness to buy its product and, thereby, identify ways to improve product to better match customer needs.

Most quality control organizations categorize defects and report them on a periodic basis. With Pareto analysis of such causes, one can lead an attack against bad quality and minimize it to the extent possible. To a considerable degree, however, the cause of bad quality lies in the original product design. Much attention is being focused on product design today—for example, employing team design involving producibility engineers to eliminate the manufacturing quality causes at the source (i.e., the product design).

During the early development of quality control in the 1920s, it became apparent that the use of statistics could aid in the search for poor quality causes (Chap. 13.6). The X-bar and R charts were developed, for example, to identify when a process was out of statistical control. By plotting the means of samples for a key variable of interest, which tend to distribute themselves according to the normal distribution because of the central limit theorem, one can identify upper and lower control limits that the sample means should rarely exceed if the process has remained in control. Such information provided a means to guide "centering" of processes to maximize the number of good items produced from the process. Numerous statistical techniques have been developed to make similar informed product quality decisions (Chap. 11.1).

OPERATIONS MANAGEMENT

Team Based

Traditional management has often been an authoritarian "do what you're told" style of management. In recent years, management has become aware that involvement leads to commitment, which leads to performance (see Chaps. 2.5 and 2.6). It has been well demonstrated in numerous applications today that team-based management, in general, provides an improved work environment. It is typically not only more productive but also, and probably more important, more amenable to a continuous improvement management philosophy.

A key to getting team-based management to work is letting employees in groups form self-directed teams where they have control over process improvements, plans, and goals (Chaps. 2.5 and 2.10). Employees instinctively want a process that is productive and they, as well, want to be productive. It is often process barriers to production and management overcontrol and overdirection that limit their motivation to produce. Workers are inherently more motivated to pursue their own goals than someone else's (i.e., management's). To a considerable degree, management needs to stop directing and controlling, and provide the team with both material and psychological support and guidance.

Continuous Improvement

As Stephen Covey demonstrates in his book, organizations need to be *learning* organizations [9]. Organizations must continuously change the way they do business so that they can adapt and become the organization they need to be to satisfy ever changing customer needs and desires (Chap. 4.2). A team-based management philosophy can provide a work environment in which change is both normal and expected. The need to adapt is probably one of the most important attributes any organization needs in order to survive in the highly competitive world of today.

FUTURE TRENDS

The work environment in the future, from the boardroom to the spot welder, will be more participative (i.e., team based), consensual, continuous improvement based, and flexible. Production processes will be more cellular in nature and suppliers will locate and develop arrangements with their prime contractors that will make the boundary between supplier and manufacturer more difficult to discern and define.

CONCLUSIONS

As this handbook clearly demonstrates, there are numerous tools available both to practicing industrial engineers and anyone else interested in applying industrial engineering techniques and methods. The most critical resource that any industrial engineer possesses, however, is his or her ability to think like an industrial engineer. The concepts of industrial engineering as contained in this handbook, whether in equation form or simply logical rationales based on sound principles, provide a solid basis for both effective problem solving and operational improvement.

Those in our society who are responsible for operational problem solving and improvement should be making full use of the many industrial engineering capabilities that exist today. The techniques, approaches, and methods of industrial engineering work equally well whether applied in a hospital, a warehouse, a factory, a depot, a supermarket, a bank, or a shipyard. Most operational improvement effort should be performed in a participative environment using employees at all levels in an organization—with industrial engineers guiding their efforts. The improvement potential in the preponderance of existing operations is enormous.

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FUNDAMENTALS OF INDUSTRIAL ENGINEERING

BIOGRAPHY

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Source: MAYNARD'S INDUSTRIAL ENGINEERING HANDBOOK

CHAPTER 1.6

THE FUTURE OF INDUSTRIAL ENGINEERING—ONE PERSPECTIVE

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Industrial engineering has evolved over the last century, constantly moving into new applications and industries using new tools—while never leaving its traditional industries. This chapter summarizes the progress industrial engineers have made over the last century and then hypothesizes the future directions of the profession.

The title *industrial engineer* (IE) has long concerned the profession because the term *industrial* may too narrowly define what the industrial engineer can and does do. There may be other words starting with the letter *I* that better capture the diversity of industrial engineering, including innovation, information, integration, implementation, instruction, involvement, and international.

Therefore, this chapter tries to expand the focus of the industrial engineering profession by recognizing that the *I* in IE may stand for many more things than the traditional term, *industrial.*

INTRODUCTION

The ability to forecast the direction of a profession is extremely difficult, if not impossible. One can use as a base the history and historical trends associated with the profession. Section 1, Chap. 1 provides an excellent summary of the principles and evolutions of the profession. As mentioned in that chapter, the context for the industrial engineering profession begins with Adam Smith and the division of labor, Eli Whitney and interchangeable parts, and James Bolton and the steam engine. These early leaders brought to the profession portions of the ingredients that we see in our industry today. Adam Smith began to address management issues critical to industrialization and employee specialization. Eli Whitney's concepts of interchangeable parts moved us out of the individualized, cottage industry to large, complex industrial and business organizations. James Bolton's portable power permitted advancements in mechanization and flexibility in siting manufacturing facilities.

Some people will say our industrial engineering history starts with Fredrick Taylor and his research in work sciences, machine-cutting techniques, and management principles. Taylor, along with Frank and Lillian Gilbreth, Henry Gantt, and others, did set the initial foundation for industrial engineering at the turn of the twentieth century. While we traditionally remember only their work in the manufacturing industries, the Gilbreths spent a considerable amount of time in all facets of society. Regardless of the industry application, that era focused on scientific management principles, work methods, and methods improvement—and the role of the professional as a consultant to industry.

Moving beyond the Gilbreths, we come to the era of operations research and the application of optimization and queuing methods to solve complex problems. We move beyond operations research to the time of systems analysis and the industrial engineer viewing problems as part of a larger system. Here we find statistics and digital simulation coming to the forefront. Continuing through time, we arrive at an era of computer automation of manufacturing systems as well as the automation of many other industries. The automation and computerization of data, converting it into readily accessible information, followed mechanical automation and created the era of information technology.

Looking back over the last century, what can we conclude? First, industrial engineering has been driven in large part by society's needs. Society was looking for a more effective arrangement between labor and management. Society was looking for an employee work environment that was safer and more conducive to worker well-being. As society began to see the larger, world picture, industrial engineers adapted by incorporating the tools of operations research and systems analysis. And finally, as society began to realize that information was of paramount importance, the industrial engineer developed and adopted tools for the information age.

Second, industrial engineers have been very adept at creating or applying new tools to new problems. Taylor applied mechanical laws to create simple machine cutting speed calculating slide rules. The Gilbreths used the motion camera and time measurement to quantify workers' activities and determine ways to improve their methods. Operations research followed new advances in mathematics and the development of the primitive computer. Movement into the information age was partly due to the advances in mainframe and personal computers and the associated computer software.

Third, our profession has constantly expanded into new industries as we continue to serve the industries we have been for decades. Taylor and the Gilbreths started in the basic metal manufacturing industry. The Gilbreths quickly moved into the health care and several service industries. During World War II industrial engineers provided invaluable services in the distribution and logistics industries to assist the Allies moving war materials from U.S. factories to battlefronts around the world. We have continued to develop tools and solutions for the distribution industry. Industrial engineering has a major presence in the overnight delivery industry as well as the traditional postal, trucking, railway, and shipping industries.

In recent years, as the population becomes older, the industrial engineer has been reacquainted with the health care industry. In addition, industrial engineers are very active in the information technology industry and dot-com companies. While we have moved into new industries, we have not moved out of the traditional manufacturing industries where industrial engineering has its roots.

In summary, it appears that from a historical perspective, industrial engineers are

- Responsive to society's needs
- Adept at creating or advancing new technical tools
- Present in nearly if not every industry in the world

So, where is the professional industrial engineer going as we move through the twenty-first century?

IS INDUSTRIAL ENGINEERING DEAD?—AN EDUCATIONAL PERSPECTIVE

From as early as the 1950s, discussion has centered on whether the term *industrial engineer* is passé or obsolete within our professional society—the Institute of Industrial Engineers (IIE). The name of the institute, as well as its direction, has been discussed on many, many occasions. Still, IIE has retained its name and continues to refer to members as *industrial engineers.*

IIE has defined the field of industrial engineering as

> concerned with the design, improvement and installation of integrated systems of people, materials, equipment and energy. It draws upon specialized knowledge and skill in the mathematical, physical and social sciences together with the principles and methods of engineering analysis and design to specify, predict and evaluate the results to be obtained from such systems.

During this same time, a number of other societies have been created or have expanded. Societies such as the American Production Inventory Control Society (APICS), the Society for Computer Simulation (SCS), INFORMS, Society for Manufacturing Engineers (SME), and the American Society for Quality (ASQ) have all expanded into areas traditionally considered industrial engineering areas. Membership to these societies is offered to many people who are not degreed industrial engineers. These people are using tools and solving problems long thought to be industrial engineering related.

There are many non–industrial engineering degrees that teach tools that have been traditionally considered IE tools. For example, the person with a bachelor's in business administration studies Taylor's Principles of Scientific Management and is very adept at applying management tools to manage technical people. A statistician with a B.S. in statistics is considered by many industries to have the necessary education to be extremely successful in quality measurement, quality control, and quality improvement. There are manufacturing technology graduates who have many of the tools necessary to design and improve manufacturing processes or manufacturing systems. Other examples are mathematicians in the operations research area, computer scientists and management information systems people in the information technology area, and mechanical engineers in the manufacturing process design and process improvement area. Therefore, many people have the educational background sufficient to be extremely effective in providing solutions to problems that have traditionally been considered industrial engineering.

Many industrial engineering schools have changed their degree names or have been created with another, but similar, degree name. Several major universities including Georgia Tech and Virginia Tech have changed their degree program names and focus to *industrial and systems engineering.* Several universities, including Cornell, have adopted the title and focus of *operations research* to wholly or partly define their degree programs. Similarly, some universities have attached the terms *manufacturing engineering* or *manufacturing systems engineering* to the IE degree title, or entirely replaced *industrial engineering* with *manufacturing* or *manufacturing systems engineering.* In addition to the technical areas, several schools have added management as a major focus and included the word *management* in their school name and degree title.

So, does this indicate that industrial engineering is dead? Or is it simply being diluted with other societies, with people that have a subset of industrial engineering skills or with degrees that represent a slightly different industrial engineering focus? Probably not. It probably indicates that the field of industrial engineering is becoming broader and broader. Industrial engineering probably grew in technical scope more than any other engineering profession in the twentieth century. Maybe this is because industrial engineering really was founded in the twentieth century, whereas mechanical engineering, electrical engineering, and civil engineering all have their roots in the nineteenth century or earlier. But, it may be that the industrial engineering profession has been more receptive to responding to society's needs and capable of adapting new tools to meet the ever-changing needs of a variety of industries.

Is industrial engineering dead? No. As a profession, it may be expanding so quickly that many other degrees and professions have expanded into segments of industrial engineering. Possibly, what is dead is the term *industrial* as a descriptor of our type of engineering. It can certainly be argued that if you consider industrial as the manufacturing base worldwide, then industrial does not fully describe industrial engineering. But similarly, nor does *civil* fully describe the civil engineering degree and profession.

IS INDUSTRIAL ENGINEERING DEAD?—AN INDUSTRIAL PERSPECTIVE

If you accept the argument that overnight package delivery, railway transportation, banking, and health care are industries, then you could accept the argument that the term *industrial* in industrial engineering focuses on all types of industries far beyond manufacturing. But many people do not think of government as an industry. Nor do bankers think of banking as an industry in the sense that automobile manufacturing is an industry. The person working in a retirement home may not think of himself or herself as working in the retirement home industry.

Even if they accept the argument that these are all industries, few people make the leap and see the need for an industrial engineer in their specific industry. Industrial engineers are assumed to be working only in the smokestack industries—in large, heavy manufacturing plants. Rarely are industrial engineers thought of as working in the cleaner, more business-oriented industries found in the service sector. Therefore, society does not think of industrial engineers as being applicable to the wide range of business enterprises in the world today.

In the early years of industrial engineering, most manufacturing companies had industrial engineering departments. Here is where most industrial engineering graduates would get their career start. The IE would remain in this department for much if not his or her entire career, rising from a junior industrial engineer to industrial engineer to senior industrial engineer. The best and brightest might become the manager of the industrial engineering department. Only in rare occasions would an IE be assigned outside the department on a permanent basis. Instead the IE would be assigned projects in other areas of the company, only to return when the project was completed.

For many years the Institute of Industrial Engineers offered a successful and well-attended IE Managers Conference where the managers of the IE departments would gather and learn and discuss how to better manage other IEs. Over time this conference has disappeared, as have most of the industrial engineering departments in most manufacturing companies. Over time, the IEs were assigned to the quality department, purchasing, marketing, manufacturing engineering, and plant floor supervision. It was found that the IE could do many of the tasks in these departments very well and complemented the skills of the other people in those departments.

Companies decided that the IE was more valuable as a member of an operational department than as a separate function. Today, there are few companies that have separate industrial engineering departments. In most cases, the functions of the industrial engineering department are still being carried out, only they are dispersed throughout the company. This has led to a loss of focus and identity for the IE in many companies. Conversely, it has led to many new career opportunities for industrial engineers. Today, IEs are accepted and are effective members of nearly all departments found in a manufacturing or service sector company. IEs have risen to the top of these departments and then to the top management positions of their companies through very different routes. An excellent example is Lee Iacocca's rise through Ford Motor Corporation—not through industrial engineering but through sales and marketing.

There have been many suggestions for new terms that would better define industrial engineering. At times, over the last several decades, the terms *systems engineer, management engi-*

neer, productivity engineer, quality engineer, and *improvement engineer* have been suggested to describe the future and direction of industrial engineering. While a title certainly does not in two or three words describe the direction of a profession, it is critical in the immediate recognition of the profession by the layperson.

The argument is not that universities that offer industrial engineering or similar programs should immediately rename their degrees. Nor is there an argument for recommending that the many industrial engineering departments within the many different industries rename their departments. Nor is it suggested that the Institute of Industrial Engineers be renamed. The argument is that the field of industrial engineering has been very broad from the beginning and is continuing to expand. The title *industrial engineering,* while possibly not very descriptive, is now recognized as a title for a very broad profession.

It is feasible to use additional adjectives to more closely define the variety of avenues and directions that the profession of industrial engineering is taking. As such, you can substitute industrial with a number of other words that begin with *I* and may better describe the future of the industrial engineering profession. By looking at how industrial engineers perform a variety of other *I* roles, it is possible to see the direction and future of our profession. Within these discussions of the different roles, you will see part and parcel of your current career or potential for your future career. Some of the *I*'s will not apply to you as an industrial engineer, but many will. You may wish to consider some additional *I*'s that better define the role that you have or will have as an industrial engineer.

INNOVATION ENGINEER

Industrial engineers, since they were first described, have been innovators. We have prided ourselves on our ability to innovate new tools and new methods to find solutions to problems. You can look back in history to see the Gilbreths' innovation, using a clock in their time studies to accurately measure people's motion over time. You can look to the operations research people of World War II using new mathematical tools and rudimentary computers to solve the issues of how to position radar units in southern England or how to distribute various cargo ships within a convoy.

A concern that has been expressed about the innovation engineer is that we have been constantly chasing the buzzword (technology fads). At times we have been ridiculed because the newest industrial engineering fad shows up in the magazines in commercial airplane seatbacks that our managers read well before most industrial engineers are aware of the fad. While industrial engineers have not been solely responsible for parading forward all the buzzwords used today, we are certainly guilty of making good use of many of them. From flexible manufacturing systems (FMS) to just-in-time (JIT) to kanban to six sigma to therblig to Pareto analysis to pie charts, we have developed our own vocabulary. In many cases these buzzwords are nothing more than new terms for old skills, or old approaches to problems or systems. In many cases society has simply reinvented a technology that was used decades earlier with a new buzzword, and possibly new software to accompany it.

For example, we now talk about the concept of bucketing production control using an automated spreadsheet system on a computer. Frank Gilbreth developed a very similar method of capacity planning using physical trays for each workstation. The trays were filled with the work packets for the parts to be made. He hypothesized that the thickness of a work packet was directly proportional to the amount of work needed to make the part. When the tray was filled to the top with work packets, the workstation was considered to be fully loaded. Obviously the trays were scaled to represent the full load of the workstation for a day or a week. Today, we estimate the amount of work needed to make the part and sum all the work assigned against the workstation on the spreadsheet until the station is fully loaded. On the spreadsheet, each column represents a station and each row represents a time period. Gilbreath used the same layout with multiple trays for the different time increments. The concept is the same, but the method to achieve the end is different, although hopefully quicker and more accurate today.

As innovation engineers, we have come to realize that we can provide industries with a competitive edge. That competitive edge comes from a number of tools and activities that are truly based in industrial engineering. Industrial engineers have been innovative in creating new tools and practices in many fields including work measurement, process improvement, ergonomics, economic analysis, facility and workplace design, material handling, management, operations research, quality assurance, and improvement to name but a few. IEs have been doing innovation since before they were first recognized as professionals.

Industrial engineers have been leaders in continuous improvement. While Frank Gilbreath said there is one best way, and we believed that for decades, we have begun to realize that the one best way today is probably going to be eclipsed by a better one best way tomorrow. We have learned that ours is a profession of change where we are never satisfied with the present, knowing that there is always a better way in the future. IEs have pioneered the concept of change management and have worked hard to make change readily acceptable, if not desired, by both management and the worker.

We have learned that changes occurring in other professions have provided us new tools and capabilities to continuously improve the systems that we address. Computer science has given us new computer and software tools. The statisticians and mathematicians have provided new computational and analysis tools. Electrical, materials, and mechanical engineering have provided us with new equipment and materials capabilities that allow us to design better work environments and facilities.

Today many industrial engineers believe in the axiom that if it was the same way last year, it is probably obsolete this year. If we are not constantly in a state of change, we are in a state of obsolescence.

In the 1960s and 1970s, U.S. manufacturing became very comfortable with their manufacturing processes. However, in the 1970s and 1980s they realized that Japanese manufacturers, who at one time were considered extremely inferior to U.S. manufacturers, had become the superior manufacturers and suppliers of choice. The Japanese were forced to improve because of their poor quality, and their improvement quickly eclipsed the quality found in the United States. This forced U.S. manufacturing, primarily the automotive and electronics industry, to quickly adopt continuous improvement and try to catch up with the Japanese. United States manufacturers became competitive once again with new innovations and the willingness to change to new processes and practices. Interestingly, today, we are seeing developing countries that have incorporated improvements much faster than the Japanese, and who are now, in some instances, eclipsing the Japanese and the United States in manufacturing quality and productivity.

Another part of innovation engineering is employee involvement. Industrial engineers have been pioneers in getting employees involved with process improvement. At one time, industrial engineers and manufacturing managers believed in the axiom that we will tell the workers not to think, and instead we will think for the workers. What we learned is that while we can tell workers not to think, we cannot, nor should we, stop workers from thinking.

What we have come to learn is that industrial engineers need to harness the employees' innovation, provide them assistance in how to implement improvement, and focus the employee involvement for progressive change. Industrial engineers have developed numerous new tools that facilitate employee involvement and today employee involvement is a standard concept that IEs employ. Please note that this concept of employee involvement was little considered only 20 years ago. Industrial engineers have been innovative and have been willing to change to adopt new concepts such as employee involvement.

A new idea for industrial engineers is the concept of partnering. Companies have realized that they cannot alone provide the customer with all that the customer expects. Companies are learning that they need to partner. Partnering allows for the sharing of expertise and resources—therefore capturing a larger market. Industrial engineers have been instrumental in helping companies determine where and how they can partner. With our experiences in systems analysis and economic analysis, IEs can quickly develop the appropriate arguments for how partnerships will be advantageous to both entities.

THE FUTURE OF INDUSTRIAL ENGINEERING—ONE PERSPECTIVE

Industrial engineers have also been innovative in the development of new information and communication tools. A theme that you will see again as you read this chapter is that information and communication are becoming major issues for industrial engineers.

An important example of innovation engineering is design for manufacturability (DfM). Manufacturability has many definitions today, but for our purpose, we will define manufacturability as the ability to design a product that can be easily manufactured, serviced, maintained, distributed, and disposed of or recycled. Obviously, manufacturability then must take a systems viewpoint and a total product life cycle viewpoint. Manufacturability then encompasses many technical areas outside of industrial engineering, including product design, environment, marketing, purchasing, distribution, etc. Therefore, design for manufacturability begins to also impact another industrial engineering area, which is the integration engineer.

Before leaving innovation engineering, it is appropriate to discuss the talents necessary to be an effective innovation engineer. Innovation does require multidisciplinary people and multidisciplinary teams. If you look back and consider the original operations research teams created during World War II, they included mathematicians, statisticians, psychologists, philosophers, as well as engineers. If people are to be innovative, they must make use of the concepts and ideas found in people with diverse backgrounds. Industrial engineers with the diverse skills associated with developing teamwork make good leaders of innovative, multidisciplinary teams.

Another trait required of an innovation engineer is the willingness to handle change. Part of change is the concept of destructive change. Destructive change is, simply put, the ability to destroy the current before you can create the new. Many people hesitate to destroy the safety of the current systems before moving to a new system. In many industrial engineers you will find a confidence to change quickly. Their ability to accept destructive change and the ability to innovate new concepts is critical. After all, how can we innovate new ideas if we are not willing to leave our old ideas and old systems behind?

INFORMATION ENGINEER

Information is driving society. It is easy to recognize that society demands that information be instantaneously available. Today, many people carry beepers, cell phones, and even palm-size e-mail computers. With these devices they get sports scores and updates on the stock market, and find out that their children are home from school and that they need to bring home milk for dinner. With cell phones people are instantly in touch with not only their families but also the entire world. While information is critical in people's daily lives, two-way communication is also critical to industry—both manufacturing and service. The design, installation, and operation of communication systems are essential for industry. The salesperson's ability to stay in touch with his or her office, as well as the over-the-road trucker's ability to communicate with the dispatcher, depends on vital communication systems that are designed and operated by industrial engineers.

In many, if not most, manufacturing industries today more money is spent on manufacturing information about the product than is actually spent in manufacturing the product. If you consider all the information that has to be captured and maintained associated with the product design (shape, dimensions, tolerances, materials, etc.), production process (processing plans, inspection processes, routings, tooling, etc.), production plan (timing, quantity, labor expended, actual tolerances and performance, lot number, lot quantity, etc.), product tracking (location and quantity), and environmental and safety issues, then you quickly begin to realize information is a major cost in manufacturing.

In some industries, information is the entire industry. This is obviously true in the telecommunications industry and the insurance industry; it is a large part of the banking industry and most distribution industries. Industrial engineers have been leaders in developing new information and communication tools that will allow industries to be effective and efficient communicators and information providers. Information and timely and accurate communication are now one of the major drivers of industrial engineers—if not all of society.

Movement of information from computer-aided design systems to computer-aided manufacturing systems to the computer-numerical-control machines is typical of automated industry. The same is true for automatic material-handling systems and radio frequency material-tracking systems. In service industries, information is regularly moved from service provider to service provider. In many cases, the primary service is knowledge based on information.

Our computer systems today are used for design, product development tracking, implementation tracking, and many other applications. Again, in many cases, industrial engineers are the leaders in designing and helping implement the information systems.

Information is experiencing a life span much longer than the life span of a material product. Automobile companies are tracking information on their customers on marketing and possible recall, dating back over a decade or more. Pharmaceutical companies, as well as foodstuff companies, routinely track all of their products until the products are in the hands of their customers.

Estimates of the amount of information that society is maintaining is truly incredible. One difficulty is that as we maintain information and technology changes, we are maintaining information in different media, many of which are becoming obsolete. Who today can still access a 7¾-in floppy disk or even a 5¼-in floppy disk? While these two media were common less than a decade ago, they are obsolete media for recovering information today and have been replaced with zip drives and writable CD-ROMs.

A large part of the need for better information technology is driven by continuously increasing government regulations. The Food and Drug Administration has developed extensive reporting and procedure requirements to ensure safe foodstuffs. Car manufacturers track customers' addresses not only for future sales but also so that timely recalls can be issued, if needed, for consumer-product safety. Now that the government is aware that we can track information on customers and on products, it is starting to require companies to maintain specific information for customer safety.

The dot-com companies are one of the fastest, if not the fastest, growing industries. They are strictly tied to the speed and convenience of exchanging information to conduct business. Certainly the industrial engineer has a role in designing and operating these systems—if not owning a major portion of the company.

What is the role of the industrial engineer as the information engineer? First, IEs have capabilities as systems designers to design the overall information system. IEs have the ability to consolidate different information systems into a single working system. With their understanding of the entire system, IEs are good at the integration of the various information areas and the development of the entire information systems. How often have IEs discovered three or more bill of material (BOM) systems within a company, all different, all requiring considerable information maintenance? How often has it been the role of the IE to bring the multiple departments together to establish a single BOM system that eliminates duplication, eliminates errors, and reduces the time from order entry to order delivery?

Because industrial engineers are also well known as implementation engineers, as will be discussed later, they are very good at helping to implement new information systems. Similarly IEs are skilled as integration engineers, capable of integrating diverse information systems.

The industrial engineers' experiences and capabilities in the areas of quality measurement and quality improvement allow them to be leaders in developing information quality systems. Industrial engineers have extensive experience in the design of quality systems for products. Industry can design a product to meet six sigma expectations, but the same is not always true for the quality of information. One of the ways IEs can be the leaders in the information age is to pioneer methods to do quality assurance on information such that the user has information that is six sigma in quality.

And finally, IEs' capabilities in employee involvement and employee training allow them to take a leading role in the training of employees as well as consumers in the accessing and usage of information. There are many roles that you will find for an industrial engineer as information engineers, and this is an area that will continue to expand. Unfortunately, it is not clear whether our undergraduate programs will adapt quickly to the new demands of the information engineer and the dot-com companies and provide the education that the IEs will need. Graduate degrees in information technology will give B.S.I.E.s additional tools that will make them successful as information engineers.

INTEGRATION ENGINEER

Industrial engineers have long been known for their skills and abilities as integration engineers. The professions that industrial engineers work in are becoming more and more complex. The people the industrial engineers work with have greater and more diverse skills. The diverse skills are important, allowing the company to be successful. Effectively, people know more and more about less and less. Therefore, the ability to integrate the activities of people with diverse skills is becoming more critical to the success of the company.

Integration of these diverse teams still has not been fully solved. The integration engineer must have a working knowledge of many old technologies as well as the new cutting-edge technologies. The integration engineer has to be able to communicate—not only in different spoken languages—but in many technical languages. The integration engineer has to use effectively many diverse communication tools, from databases to project management tools to graphical interfaces.

The key ingredient in integration engineering is the ability to understand the systems aspects. The ability to integrate diverse systems from microsystems to macrosystems is becoming increasingly important. In addition, the integration engineer must integrate human, mechanical, and computer systems. Many computer systems, because of varying system ages, are difficult to integrate. The integration engineer must enable these systems to work together effectively, knowing when the systems can be isolated and when the systems must be integrated.

The industrial engineer is using new systems and new, advanced tools. Some of these tools such as queuing models and operations research have been around for decades. But new tools including visual simulation with object-oriented programming and graphical user interfaces, along with animation, are the new tools of the twenty-first century. In addition, extensive statistical analysis and computer analysis tools are critical to systems analysis and integration.

The integration engineer integrates the diverse skills of the other technical areas. He or she also addresses the systems aspect of the project and effectively uses team building and consensus building to bring diverse people together. To be an effective integration engineer, one must have a wide and varied educational background. Not only do IEs have to be skilled in the industrial engineering discipline, but they must also be knowledgeable in many, if not all, of the other engineering disciplines—as well as disciplines outside of engineering.

The truly effective integration engineer has had course work in materials science, engineering mechanics, system control, thermodynamics, heat and mass transfer, and electronics. The integration engineer also has to have strong knowledge in the physical and biological sciences and the humanities and social sciences. The effective integration engineer must have exceptional communication skills (verbal, written, and graphical), as well as skills of persuasion. The integration engineer must also understand business systems, finance, accounting, and project management. Above all, the integration engineer must understand the concept of a system and be able to integrate smaller systems into larger systems and divide larger systems into smaller systems.

IMPLEMENTATION ENGINEER

Industry is beginning to realize that life cycle engineering is critical for product development, manufacture, and disposal. Life cycle engineering includes every aspect of a product's life or service's life from the basic product or service concept to the product's final disposal or reuse. But, life cycle engineering goes beyond the basic engineering, manufacturing, and distribution of the product. Life cycle engineering also includes marketing, forecasting, finance, environment, and communication and persuasion. As with integration engineers, the implementation engineer must work with people with diverse backgrounds.

The person that is doing the basic product design will, probably, have very little knowledge about manufacturing processes, and even less knowledge about distribution and final products disposal. The person developing the marketing necessary for successful product sales may have little understanding of the manufacturing processes. The financial analyst who determines the viability of the product will have little knowledge of the environmental issues and product disposal issues. But the IE can be an effective implementation engineer following and managing the product or project from concept to completion.

Industrial engineers have the economic, finance, accounting, and business skills necessary to communicate with the nonengineer associated with the product life cycle. IEs also have the necessary skills to work with the suppliers and purchasers, and the government compliance agencies and regulatory bodies. A key emerging issue for the implementation engineer is to work with implementations across country boundaries, assuring that the product meets all of the various country regulations, import/export requirements, and languages necessary for the product to be used in various parts of the world. Here the implementation engineer also becomes the international engineer.

Another major issue of implementation engineering is the ability to work at the plant floor level with the hourly manufacturing personnel. The industrial engineer may be working with manufacturing personnel on factory floors, both in the United States as well as in the Pacific Rim, Europe, or Central and South America. For IEs to relate well to people on the plant floor, they should have effective communication skills and understand the motivation of the manufacturing plant floor worker.

Implementation typically also means adherence to a schedule and to a budget. The IEs' skills in project management are important to implementation and result in the ability to complete the implementation on time and at budget.

Many of the implementation skills are not taught in universities today. Unfortunately, many of the critical implementation engineering skills are learned through hands-on experiences, and while difficult to acquire, can be acquired with time. Some universities are beginning to address the issues of implementation skills; their courses are focusing more on industrial applications and less on simply learning the tools. But implementation is a skill that requires mentoring, utilization of diverse tools, and experiential learning. Again, another of the reasons why many industrial engineers are excellent implementation engineers is because they have had the opportunity to acquire diverse experiences through working in many different departments in the company.

INVOLVEMENT ENGINEER

The involvement engineer is the industrial engineer who is a team leader, facilitator, manager, unit leader, or consensus builder. Many companies are taking the viewpoint that they will minimize the number of managers and push the decision processes back to the hourly workers. It is not reasonable to expect that the hourly workers can immediately grasp the importance and responsibility associated with accepting management and leadership responsibilities. Instead, it is critical that there be industrial engineers involved with these work teams, teaching them the skills necessary to be an effective, self-managed group, and teaching them the skills to become improvement engineers. Much of the work the IE will do will be as a mentor or facilitator helping the team be more effective. In some cases the IE will assist by doing some of the more difficult, analytical analysis for the team.

Involvement engineering may become the old management engineering. The effective involvement engineer has excellent communication skills so he or she can convey not only data but also information and eventually knowledge. The effective involvement engineer can build consensus, thereby facilitating implementation and effective change. And finally, the effective involvement engineer is an instruction engineer, good at training and instruction. It is critical that the hourly workers who are going to be self-led and implementing improvement and change have the basic skills so that they can be effective.

Therefore, the industrial engineers are doing less on their own and more as leaders of teams. The result is that many more people are using industrial engineering skills, but these people do need to be supervised so that they do not misapply or misuse these skills. It also means that the industrial engineer is facilitating people's work versus doing their work for them.

There are other areas where IEs have gotten involved. The areas of human workplace interaction, human factors, ergonomics, and workers' safety are critical areas where the industrial engineer is involved with the worker. Over the last several decades, we have learned that for a company to be cost competitive and to be worker friendly, they must design processes and products that consider the worker and user. Industrial engineers are involved with the design of those processes and products so that they are user friendly.

INSTRUCTION ENGINEER

As more responsibility is assigned to the hourly worker, it is becoming apparent that these workers would benefit from some management training. The industrial engineer is becoming the instruction engineer of the future. We are getting more involved with the training of people. The industrial engineer develops the training material, in many cases interacting with the people who have the core knowledge. The IE helps determine the critical core knowledge, organizes that knowledge, and presents that knowledge in a logical flow. Industrial engineers develop the training materials, examples, and appropriate exercises. Industrial engineers are also involved with the development of the outcomes assessment tool to determine whether the people have been effectively trained. The IEs also will be involved with the development of the training facility and the economic analysis to determine whether the training has an acceptable return on investment.

Industrial engineers are well known for their ability to train the trainer. It has been found that it is, in many cases, more effective to train a group of people to be the trainers, and then allow them to interact directly with the people needing to learn. Therefore, the IE in many cases trains the trainer, supervises the trainers, and oversees the trainers' performance. But, industrial engineers are also the trainers themselves. Given the IEs' strong communication skills and organizational skills, they are effective trainers.

It cannot be overemphasized that it is necessary to develop effective measurement methods to determine if the training was successful. Industrial engineers have the skills in management and human factors to determine if the workers have effectively learned the material. As implementation engineers, they are effective in helping the trained people assimilate the information and apply it in their workplaces. The industrial engineer will start off as an instruction engineer and, after the instruction is complete, become the implementation engineer assisting the workers apply what they have learned.

Unfortunately, many industrial engineers do not receive much education in regard to being an instruction engineer. IEs as undergraduates receive education and experience developing effective presentations, but they rarely receive training on how to develop learning materials, teach, and measure learning accomplishments. Typically, IEs have gained this skill through intuition, observation, or continuing education.

INTELLECTUAL ENGINEER

An intellectual engineer is a person who understands that technology is critical for solving problems, that technology is constantly evolving, and that time and energy must be invested to stay current with the most effective technology. It is not the purpose of this chapter to argue that only industrial engineers are intellectual engineers. Rather, industrial engineers because of their diverse roles must be especially aware that they need to stay current with the technology that is available to them.

It has been argued that an engineer has a "half-life" of somewhere between 4 and 6 years. That is, half of what an engineer has learned in college is no longer applicable to what he or she is doing roughly 5 years after graduation. In another 5 years, for a total of 10 years after graduation, only 25 percent of what the industrial engineer learned in college is still applicable either because it is obsolete technology or because the IE's job function has changed such that the IE education is no longer applicable. Another 5 years finds the IE down to only 12.5 percent, and so it goes.

To combat this loss in capability, the IE has to be an intellectual engineer and develop his or her own plan to stay current with the latest technologies. The IE has to learn how to learn independently. This learning can be acquired through advanced degrees, in-house training, external seminars and short courses, or active participation in professional societies. Many companies have eliminated their in-house training and cut professional enhancement from their budgets. It is now up to the industrial engineer to determine a plan for upgrading their capabilities, invest the time and money needed to upgrade, and establish an aggressive plan for staying current. Only then can the industrial engineer say that he or she is truly an intellectual engineer.

INTERNATIONAL ENGINEER

Nearly every company in the world today is an international company. While it may have its entire operations in only one country, it probably either ships products to a different country or purchases raw materials from a different country. Many manufacturers of consumable products now print their instructions in three to five different languages. Because the companies of today are truly becoming international, the industrial engineer must be an international engineer.

The industrial engineer must be able to apply his or her skills worldwide. An industrial engineer may very well be putting together a standard package that will be used in manufacturing facilities in two or more countries. The processes that they have designed may be used in more than one county. Many companies are developing teams for implementation that have people with varying cultural and geographic backgrounds. Industrial engineers, as true international engineers, must be able to facilitate and lead these diverse teams.

There are special skills required to work in the international arena. The industrial engineer must be cognizant of the issues of professionalism and ethics that vary from country to country. In addition, the industrial engineer must be aware of the different customs and work habits and patterns of people from around the world. International politics and international laws as well as varying environmental constraints make the industrial engineer's work extremely complex. The necessity of communicating in different languages, across different time zones, and using different software make the international arena and international engineering even more complex and difficult.

In most universities, very little is taught to the industrial engineering student about how to be an international engineer. But, in many universities in the United States, not only the graduate but also the undergraduate population is made up of many non-U.S. students. While international engineering might not be specifically taught as a subject in industrial engineering curricula, there is certainly the opportunity for the undergraduate and graduate student to learn from their peers about international issues.

Although the world is a large place, we are quickly learning that the effective industrial engineer, who will grow within his or her company, must truly be an international engineer prepared to work anywhere in the world, take his or her family anywhere in the world, and enjoy the opportunity to be that true international engineer.

WHAT HAVE THE I'S MISSED?

Have the *I*'s captured all that an industrial engineer is or will be? Definitely not. As you read these pages, I am sure you thought to yourself that certain areas where industrial engineers have been successful have been missed. There are investment engineers considering the financial issues. There are incorporation engineers who are entrepreneurs starting new companies.

Certainly, industrial engineers have been leaders in the quality revolution of the last twenty years. They have helped to design products and processes that have resulted in the ideal product, service, or distribution systems. Possibly, they have become the "ideal engineer."

Many industrial engineers have become leaders of their organizations. They have used their industrial engineering skills to become successful managers. You can argue that a major component of being a good leader is providing the inspiration to the people you manage so that they strive and accomplish more than even they believe that they can. In that sense, industrial engineers who are successful managers are inspiration engineers.

There are areas where the industrial engineer has been successful that this chapter has not mentioned. Hopefully, the reader will be able to describe many more, with or without an *I*. Many of the *I*'s overlap. These are not clearly defined, small niches for the IE. Rather, many IEs function across many of the *I*'s.

The one thing we are certain of in regard to industrial engineering is that the future will be different than the present. We know that industrial engineering has been constantly evolving over the last 100 years. The curriculum that is offered by industrial engineering or similarly named programs around the world has been constantly changing. Industrial engineers have found new roles in new industries on a regular basis. Today, there are IEs in every industry in every corner of the world.

Industrial engineers have always worried about their image and recognition of their profession. It is possible that the inability to be fully recognized is because industrial engineering is a profession that is constantly changing and evolving. It is also possible that the image is not crisp because the IE has so many diverse roles in many different industries. From a layperson's viewpoint, a medical doctor works in a medical facility helping to make or keep people well. The role of the physician is fairly crisp and well defined. Unfortunately, for our concern about the IE's image, our multiple roles result in our image being hard to define for industry or society. Fortunately for IEs pursuing careers in our profession, the multiple roles provide wonderful opportunities for IEs worldwide.

What is clear is that there is little in any area that is even remotely related to industrial engineering that is not industrial engineering or can be done by an IE. One thing is true about industrial engineering: if you define it as industrial engineering, it is industrial engineering. If it is not industrial engineering today, it will probably be industrial engineering tomorrow. An industrial engineer, now long since passed away, once said that industrial engineers find problems, find tools to solve the problems, and solve the problems. That part of industrial engineering will not change. How we solve the problem, what tools we use to solve the problem, and the problems we address will change—but we will always solve the problem.

ACKNOWLEDGMENTS

I wish to thank my father, Dr. James H. Greene, a career industrial engineering educator who helped me understand what an industrial engineer is. I also thank the people who taught me my own skills—my teachers, my colleagues, and my students. Considerable insight came from John Powers, retired from Kodak and now executive director of the Institute of Industrial Engineers, and Dr. John J. Jarvis from Georgia Tech, current president of IIE.

BIOGRAPHY

Timothy J. Greene, Ph.D., is the dean of the College of Engineering and professor of industrial engineering at the University of Alabama. Prior to joining the University of Alabama, he was the associate dean for research in the College of Engineering, Architecture and Technology at Oklahoma State University from 1995 to 1999 and professor and head of the School of Industrial Engineering and Management from 1991 to 1995. In the 1980s he was associate professor and assistant department head in the Department of Industrial and Systems Engineering at Virginia Tech. Dr. Greene received a B.S. degree in astronautical and aeronautical engineering from Purdue University in 1975. He also has an M.S. and Ph.D. from Purdue University in industrial engineering, receiving his doctorate in 1980. The Institute of Industrial Engineers recognized Greene in 1986 with their Outstanding Young Industrial Engineer Award. He served as president of IIE from April 1997 through March 1998, and in 1999 he was selected Fellow of the Institute. His expertise is primarily in scheduling, computer-integrated manufacturing systems, and change management.

Source: MAYNARD'S INDUSTRIAL ENGINEERING HANDBOOK

CHAPTER 1.7

FUTURE TECHNOLOGIES FOR THE INDUSTRIAL ENGINEER

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This chapter examines the future of industrial engineering through an assessment of the technologies fundamental to our profession. The assessment addresses changes in information technology, simulation technology, and virtual reality approaching, and going somewhat beyond, the year 2010. The continuing rapid advances of computing performance and Internet capabilities will combine to provide global access to information for modeling and analysis. Object-oriented simulation will provide a mechanism for development of increasingly complex distributed models. Virtual reality will facilitate the development of virtual processes and factories for analysis and actual operation. The fusion of these technologies will vastly improve the way industrial engineers integrate systems and components for efficient and effective use by humankind.

BACKGROUND

Predicting the Future

Throughout history most civilizations have pondered the future. The calendar is one of the earliest records of prediction, among other things providing a guide for planting and harvesting. But whether through calendars, prophets, astrologers, fortune-tellers, or sages, the quest to predict has been consistent. It only takes a quick Web search using the word *futurist* to find a plethora of organizations and individuals prognosticating the eventuality of all things imaginable. Predictions can be found for space exploration, life longevity, social structures, climate, and technology, to specify a few. However, predictions of the future are volatile and subject to the chaotic happenings of life and even sometimes the apparently insignificant flap of a butterfly wing. History has shown us that change is constant and inevitable. Forecasting, for the most part, is based on the past, and it is only when the future becomes the past that there is complete certainty. The past also is a record of the unexpected, of the richness of human innovation, and of the surprise of significant breakthroughs. One use of prediction is to prepare for changes that the future will bring. That is the purpose of this chapter: to provide today's industrial engineers with a prospective vision of tomorrow, possibly as a guide for preparation and possibly as a catalyst for change and innovation.

Scope of the Assessment

There is an overabundance of likely advancements that will have significance to the future industrial engineer. These include advancements in theory fundamental to the profession. Hundreds of monthly publications document these incremental advancements. However, it is extremely difficult to *predict* major advancements in theory. Many of the advancements over the next decade will likely come from the integration of sciences and technology. There will also continue to be advancements in the efficiency and productivity of many of the established technologies. One of the technologies basic to industrial engineering is information technology. Gathering data, modeling systems, and analyzing results all rely in some way on information technologies. Computing technologies and communication technologies are fundamental to the advancement of information technologies. We will begin by looking at the future of these technologies. Resulting from these technologies will be the development of many information technology–related products. A vision of future information products through the eyes of some corporations and laboratories will be presented. Through this vision, it will become apparent that the advancements in information technologies and products will significantly facilitate the use of simulation and virtual reality for the modeling and analyzing activities of the industrial engineer. Since manufacturing constitutes the largest single sector of the industrial engineering profession, particular attention will be paid to the future of manufacturing. This assessment is based on university, government, and industry sources to project technological advances as we approach the year 2010. In cases of significant advances, some projections beyond 2010 have been included. The timetable for some of these projections will likely be in error. Regardless, a good projection of the direction and speed of advancements should persist. Many of the references cited include http URLs (uniform resource locators). It is also likely that some of these URLs will cease to exist. However, URLs are rapidly becoming a significant source of information. Since this chapter addresses the future, these volatile references are included.

Today's Industrial Engineer

The industrial engineering profession is perhaps more diverse that any of the other engineering disciplines. Among us you will find engineers working in facilities design, work methods, simulation, human factors, production planning, operations research, information systems, and many other areas. The Bureau of Labor Statistics's Online Occupation Outlook Handbook indicates that there were approximately 115,000 practicing industrial engineers in 1994 [1]. Of these more than 75 percent were employed in the manufacturing sector with the remaining employed in utilities, trade, finance services, and government. The discipline is expected to grow by 10 to 20 percent per year through the year 2005. This means that there will be between 328,000 and 854,000 industrial engineers at that time. By the year 2020, when most of the advancements discussed will be realized, a 20-year-old industrial engineer (or student) in 2000 will be 40 years old. Because of the high percentage of industrial engineers in the manufacturing sector, it is likely that the outlook for industrial engineering will be highly correlated with the future of manufacturing. In general, most industrial engineers are concerned with the design and integration of system components such as people, equipment, facilities, and methods to create and improve efficient and effective systems that produce goods and services beneficial to humankind. Engineering is the application of science to model, analyze, and solve problems. The standard sciences of the industrial engineer are mathematical, statistical, and computer sciences. Common modeling and analysis techniques include optimization, stochastic process, simulation, economic analysis, production planning, forecasting, job analysis, and facilities design. The diversity of the discipline requires that the industrial engineer be adept at locating information and collecting model design and input information. Computer technology and tools facilitate our modeling and analysis, providing

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us with a means of visualization and rapid computation. Communication technology and tools facilitate information collection and dissemination. These are the technology advancements discussed in the following sections.

INFORMATION TECHNOLOGY

Computing Performance

For some time now semiconductor price/performance has doubled about every 18 months. This phenomenon is called *Moore's law.* And while there has been some healthy skepticism that this phenomenal growth can continue at this pace, there is no evidence of a slowdown. Projections of information technology and performance to and beyond the year 2010 are shown in Table 1.7.1.

In late 1999, 500-MHz processors were projected to be in a majority of the more than 90 million personal computers that will be sold [2]. New processor architectures will also increase the speed of moving data chunks by a factor of 16. At the workstation level, it was predicted that processor speeds would reach 1000 MHz by the year 2000 [3]. If it is assumed that performance alone will continue to double every 18 months, in 10 years personal computers should see performance increases between 64 and 128 times that of today. There is some evidence that the performance increases could be significantly higher than this even. IBM is currently conducting research into quantum computing at room temperatures [3,4]. It is projected that this technology could be commercialized as early as within 10 years, increasing computing speed up to 1600 times that of present day CPUs (central processing unit) [3]. The world's fastest supercomputer developed under the Accelerated Strategic Computing Initiative program by the U.S. Department of Energy in cooperation with Sandia National Laboratories [5] operates at over 1

TABLE 1.7.1 Projections of Future Information Technology

Technology	Toward year 2005	Toward year 2010 and beyond
Computing technology	1999: 500-MHz microprocessors 2000: 1000-MHz workstations 2005: 1000–2000 MHz microprocessors 2000: 128-Mbit stamp-size memory cards 2001: widespread use of 400-Gbit 1-inch platters	2008: 10 Tflop supercomputers 2009: 1 million processor parallel computers 2010: 64–1600 increase in microprocessor performance 2013: 1-Tbit memory chips 2014: VLSI 256-Gbit chips 2017: 100-Gbit erasable RAM 2018: 1-TIPS microprocessors 2018: 10,000 cell biocircuits
Internet technology	2000: 327 million Internet users 2001: affordable 10-Mbit modems 2002: 1-Tbit fiber-optic speeds 2002: $1.2 trillion Internet economy 2005: on-demand global multimedia	2009: affordable 150 Mbit connections 2009: household optical fiber 2010: 1–2 billion Internet users
Wireless technology	1998: 2-Mbit wireless LANs 1999: worldwide access voice communication 2000: 64-kbps Internet with satellites 2003: over 1000 communication satellites 2005: 155-Mpbs communication	2010: radio waves offer millions of simultaneous local connections over 100 Mbps 2011: widespread 100 Mbps global access

TFLOPS (tera floating operations per second). In this initiative nuclear testing and manufacturing will be completely simulated. Eventually personal computers will also reach these speeds, but this is not expected to happen until somewhere around the year 2018 [6]. Long before this, around the year 2012, personal computers are predicted to run on a button-sized battery without replacement for a full year. In the year 2008, it is projected that supercomputer speeds will reach 10 TIPS (trillion instructions per second), and at about the same time there should be practical use of parallel computers housing over 1 million processors [6].

Significant advances have also been made in computer memory and data storage. In the early 2000s there should be 1-in 400-Gbyte memory platters [7] capable of holding up to 5 hours of audio and video, and it has been predicted that there will be a postage stamp–sized memory card capable of holding more than 200 hours of audio and video by the year 2005 [8]. Even simple linear forecasting from the 1980s would predict extremely small memory devices, perhaps the size of pencil erasers, holding over 1 Tbyte of information, which is enough memory for 10 to 20 hours of video and audio as we reach the year 2010. The Japanese government's 1997 technology forecast predicted memory capacity of 1 Tbit per chip by 2013 and VLSI (very large scale integration) with as much memory as 256 Gbits per chip by 2014 [6]. For the industrial engineer, these advancements in computation will significantly impact the time required for conducting optimization and simulation analysis.

Internet Technology

In 1998 there were more than 100 million people around the world using the Internet [10], and this grew to 304 million users in the year 2000 [9]. From 1997 to 1998, there was approximately a 1000 percent increase in Internet use [11]. There are also over 200 million http:// URLs. Currently Internet traffic is growing "a hundredfold every 1000 days [12]." More and more people are relying on the Internet as necessary for their work. Not only has e-mail communication become an essential part of business, but there is also a rapidly growing Internet commerce. PricewaterhouseCoopers reports Internet commerce in 1998 was about $78 billion [13]. Nicholas Negroponte, the director of Massachusetts Institute of Technology's multimedia lab suggested that Internet commerce would reach $1 trillion in the early 2000s [12], while other forecasts were not so optimistic [14]. It is very difficult to forecast 10 years into the future of the Internet with much reliability since the data is so sparse and the trends are so recent. However, at current rates of increase there should be 1 billion connected users with an Internet economy of thousands of trillions of dollars by the year 2010. At some point the rates should slow down, but that time is not yet foreseeable.

The predicted increases in Internet use also depend on increases in the speed of interaction (including uploading and downloading). In the late 1990s, most home users connected to the Internet using modem technology. In the early 1980s, a typical modem or acoustic coupler operated at a speed of 300 baud (bits per second [bps]) over conventional copper telephone lines. By 1985 modems were routinely operating at speeds of 1200 baud, which grew to 14.4 K baud by 1996. In 1998 the speed of conventional modems increased to 56K baud with special xDSL (digital subscriber line) modems starting to enter the market. The use of 56K modems by online homes and offices was approximately 50 percent by the end of 1998 [2]. The xDSL modems require infrastructure changes by phone companies that many companies have already made. There are several standards in the xDSL family with ADSL (asymmetric digital subscriber line) being the implementation of choice. ADSL modems were operating at speeds of 1.5 Mbps (megabits per second) in 1999 according to an Internet news source [15], the same speed as T1 lines. In the early 2000s there will be 10-Mbit ADSL modems in use, working over copper phone lines. Currently cable modems that operate over cable television lines are designed to reach speeds of 10 Mbps. Widespread use of systems facilitating on-demand acquisition of multimedia information dispersed on networks around the globe is expected to be in place by the year 2005 [6]. Many of the cable companies are now either using, or are changing to fiber-optic lines. Also about 5 percent of the copper telephone wiring is replaced with fiber optics every year [11]. In 10 years a majority of the copper infrastructure will have been replaced by fiber-optic cable.

In 1977 the first tests of live telephone traffic using fiber optics was conducted by General Telephone and Electronics at speeds of 6 Mbps. By 1997 Bell was using 45-Mbits/sec fiber speeds and today one fiber can carry 10,000 Mbps. Experiments are being conducted with fiber speeds of 1 Tbit/sec [3], likely to be in use in the early 2000s. At speeds of 1 Tbit/sec, all of the current Internet traffic in the world could be carried on one fiber, every edition of the *Wall Street Journal* could be downloaded in less than 1 second, or over 1 million channels of television could be simultaneously broadcast [12]. And all of this data is transmitted on a single fiber. Household use of optical fibers is predicted to be affordable (under $400 for a transceiver) by the year 2009 with widespread use of high-capacity networks having capacities of 150 Mbps [6]. As these speeds are realized, the Internet will offer global real-time interaction that will increase the necessity of using the Internet as an important work tool. Industrial engineers, as well as others, will have greater and faster access to information. Real-time interaction will facilitate interactive, distributed modeling, and analysis among multiple users.

Telecommunications Technology

In 1965 the first commercial communications satellite was launched into orbit, capable of handling only 240 voice circuits. This had grown to around 220 communications satellites in mid-1998, and by 2003 there is projected to be over 1000 communication satellites beaming voice and data communications to every part of the world [16]. Numerous applications of satellite communication technology exist. The Global Positioning System (GPS) is a well-known example consisting of 24 satellites that orbit the earth. GPS can now locate a three-dimensional position under a meter in length with the aid of ground-based systems. Some GPS applications that have recently been noted include mapping and surveying systems, navigational guides for motorists, airplane traffic control, remote monitoring of machines, and alarm systems [17]. Paging communication is another example. In 1998, approximately 30 percent of U.S. households used pagers, or 1 in 6 Americans [17].

Satellite voice communication, however, is typically used only for international phone service where fiber-optic cable has not been installed. This is because most communication satellites have orbited at about 36,000 km, which is required for a geosynchronous orbit where the satellite remains in a stationary position relative to the earth. These satellites are known as GEOs (geosynchronous earth orbit). The problem with GEOs for voice communication is that there is a 0.25-sec propagation time for signals to travel to and from the satellite, causing minor delays in voice communication. Over the next 6 to 7 years a large number of lower earth orbit (LEO) and midearth orbit (MEO) satellites will be put into service [18]. There are two important advantages in using LEO and MEO satellites. First, the signal propagation time is significantly reduced. For example, signal propagation to a satellite orbiting at 1500 km (LEO) will take several hundredths of a second. Second, the strength of the signal falls with the square of the distance from the satellite. So a satellite orbiting at 10,000 km (MEO) would receive a signal 13 times stronger than a signal from a 36,000-km (GEO) satellite [18]. This is important for data communication, but perhaps more important for voice communication.

More than 50 million Americans use cellular phones [19], which is approaching 40 percent of U.S. households. Most current systems rely on proximity to data hubs that transmit and send calls. One of the most important benefits of the new LEO systems is that they open the possibility of complete global communication from a handheld device, without communication through a data hub [16]. LEO systems can communicate directly with the cell phone because the signal needed to communicate is sufficiently low not to injure the user, whereas GEO systems would require much stronger signals. An example is the recently deployed Motorola Iridium system with 66 LEO satellites orbiting at 780 km, and others are close behind [18].

Satellites will also compete for data communication and the Internet market. The Direct Broadcast Satellite (DBS) currently operates at a maximum rate of 12 Mbps. Newly planned data-oriented satellites will have capacities of up to 10 Gbps. Individual subscribers will be offered data rates from 64 kbits/sec eventually reaching 155 Mbps [18]. These rates do not compare with fiber-optic rates and probably the fastest connections will be wired unless satellites that communicate with light beams are developed. However, Internet via satellite will provide global Internet through devices such as cell phones that handle Internet, fax, messaging, and voice communications in a handheld device [19]. There are other plans to bring satellites down to the level of floating balloons at even lower orbits [8].

Wireless ground-based communication is also coming of age. In 1998, Carnegie Mellon University had a wireless network that serviced about half of the students [19]. This network operated only at 19.2 kbps but provided students with the ability to use a laptop for network connection almost anywhere on campus. Multichannel multipoint distribution service (MMDS) is another wireless approach using microwaves reaching communication speeds of 800 kbps. There are other local area wireless networks operating at speeds as high as 2 Mbps [19]. And in the future many people will have access to wireless communication through radio waves where information will be parceled into digital bundles. Studies have been conducted that have theoretically shown that "millions of radio transmitters within the same metropolitan area can successfully operate in the same frequency band while transferring hundreds of megabits of data per second" [20]. Widespread use of portable multimedia wireless terminals operated on the order of 100 Mbps, which can be used throughout the world, is predicted to be available by the year 2011. These technological advances will spawn the development of numerous new information technology products.

FUTURE INFORMATION PRODUCTS

Vision of the Future Project

While the majority of companies prefer to keep plans for future products proprietary, Philips Design has made public through electronic journaling its "vision of the future" project aimed at prospective information technology and merchandise for the year 2005 [20]. With a vision of creating tools for an efficient, environmentally conscious, sustainable society, Philips has proactively attempted to prognosticate and conceptually design information-based solutions for the impending social, cultural, and intellectual needs of such a society. Many of the resulting innovative tools are certainly intriguing, but equally noteworthy are the methods employed to determine this future.

Philips began its design process by gathering information from trend-forecasting institutes. Many such institutes can be found on the Internet [e.g., Refs. 22–26]. Through such futurist sources a voluminous store of information is obtainable, and the determination of its specific relevance could be a daunting task. Satiated with futurist data, Philips's approach was to organize several multidisciplinary teams consisting of "cultural anthropologists, ergonomists, sociologists, engineers, product designers, interaction designers, exhibition designers, graphic designers, and video and film experts." These teams were used to filter the information into conceptual product scenarios. The teams participated in a series of creative workshops that produced 300 of these product scenarios, or short stories, describing the futuristic products and their use. These 300 scenarios were filtered again and again down to a set of 60 product concepts. At this point Philips organized a panel of leading futurists from around the world. The concepts were presented to them for comments and advice. The results were distilled into conceptual product designs found in the Philips *Vision of the Future* virtual journal [20].

Many of these conceptual future tools have obvious implications for the workplace. Among these are interactive wallpaper, magic pens, creativity mats and wands, information hearts, data zones, the Shiva, immersion goggles, and remote eyes. Equally intoxicating are the hot badges, media dispensers, scanners, interactive books, makeup boxes, and interactive jewelry. Merely the names of some of these products should intrigue even the utter skeptic. However, some of the

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forthcoming descriptions may appear to come from our current cultural fascination with science fiction. Yet, all of these products have been deemed technologically feasible and socially desirable in less than a decade. Time will tell whether they become economically accessible.

The Medium for Meetings

Critical to most industrial engineers is communication. Our discipline is not particularly conducive to solitary labor. And most of us are well practiced in the art of meetings. This will probably not change; however, the medium may. The typical medium for most meetings consists of whiteboards, transparencies, and perhaps computer display devices largely used for better presentations. Interactive wallpaper is the starting point. Interactive wallpaper is predicated on the continuing advancements and economics of thin or flat display devices. Conceivably many or all of the walls in a room could consist of such displays that can be configured for pure aesthetics. It is predicted that by the year 2014 displays will not only be thin, but also capable of being rolled up [6]. Aside from altering the interior decorating workforce or owning a television that can display many concurrent programs wherever the wallpaper is hung, the displays also can be used interactively. Imagine all of the walls being partitioned for presentations or team-based design sessions. Of course, such a complex of partitions would require coordination, or in the Philips world, the use of an *information heart.* This device would be the master control used to coordinate the walls and to assign specific inputs and outputs to each interactive zone, to provide access authorization, or completely change the zones. Interactive wallpaper merged with digital imaging, video conferencing, and real-time Internet interaction will facilitate meetings with participants from around the world reducing the need for business travel.

The magic pen doubles as a writing instrument and a recording device that captures the output of the pen as one writes and sketches. The magic pen could be used to capture meeting notes that can be downloaded to a computer later, but could also be used interactively within the meeting. And there are greater advantages than eliminating the necessity of locomotion between the boards, displays, and projectors. Notes and diagrams produced from one's immediate area of accessibility might be used to dynamically interact with the presentation, either on individual wall zones or in a collective sense on a common wall zone. This opens up the possibility of a highly interactive meeting and changes the nature of meeting notes. Ideas could be more easily merged and modified, with an information heart and moderator handing off zone control as the meeting moved from idea to idea. Likewise facilitated would be group breakout sessions. Along with the magic pens are the creative mats and wands. In the Philips conceptualization, mats and wands were designed for children. They serve as an interface for playing games and for multimedia creations, such as personalized stories. In the workplace each individual may also have a mat and a wand. The mat is an input device, conceivably for both the magic pens and the wands. The wand would be used as an interface to build or display animations, simulation, and add audio enhancements to the output of the magic pens, functioning almost similar to a remote control device for interacting with anything on the display. It would seem that the creative play of children should not be too far removed from the creative work of engineers. Some conceptual designs of magic pens and wands produced by Philips are shown in Fig. 1.7.1.

To Mitsubishi Electric interactive participation will take place over networks, making meetings and design more accessible from remote locations, including the possibility of navigation and interaction with 3D-created worlds [27]. While there may be a tremendous market for this type of tool in the entertainment industry, it is also very useful for engineering. Similar commercial software technology tools have already been produced. With these products the image of each interacting person resides in a visual 3D artificial world. The person may navigate through this world, visualizing and interacting with objects, including other people. Although this technology would have many uses for entertainment and gaming, an obvious industrial engineering application is in the area of facilities design. One can also imagine navigating through a plant to a problem area or machine where real-time or historical animation of the process is witnessed by a

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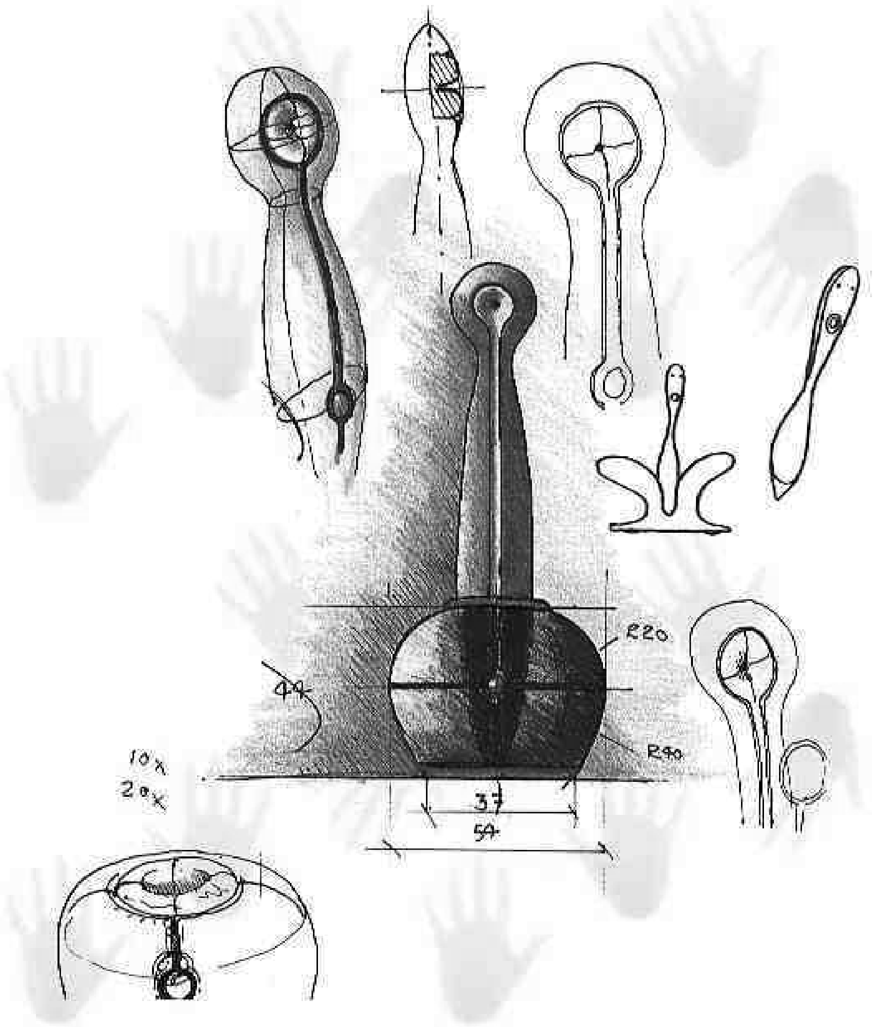


FIGURE 1.7.1 Conception of wands and magic pens. *(From the Vision of the Future Project conducted by Philips Design, Eindhoven, The Netherlands. Used with permission.)*

team, or similarly navigating through a design, a process, or simply discussing ideas while visualizing the subject domain. In these 3D worlds, meetings take on an entirely new dimension.

Working from Remote Locations

Immersion goggles are an extension of head-mounted displays discussed later. While interaction with 3D virtual worlds might not require the use of such goggles, these goggles would provide visualization capabilities nicely suited for remote locations. Another perceived application is in the area of control of robotic systems. Goggles might be conveniently located next to data zones and in meeting rooms, or personally taken to a remote location. Another manner of providing input from a remote location may come from remote eyes. Remote eyes are small wireless cameras, which will inevitably raise serious security and privacy concerns. Similar to the cameras that are attached to computers today, these cameras may be conveniently moved to problem locations or carried to the far reaches of the planet. Coupling remote eyes with 3D worlds, interactive wallpaper, and an information heart could provide an intriguing workplace for a plant analyst. A depiction of remote eyes is shown in Fig. 1.7.2.

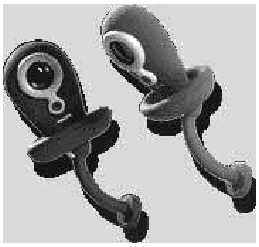


FIGURE 1.7.2 Conception of remote eyes. *(From the Vision of the Future Project conducted by Philips Design, Eindhoven, The Netherlands. Used with permission.)*

The Shiva is a multitasking personal assistant for information gathering, communication, and entertainment. The name *Shiva* comes from the Hindu god with many arms, apparently representing the multifunctional capacity of the tool. For some time personal assistants have been available on the market. Acceptance in the United States has not been as fast as in other countries, such as Japan where the electronic districts sport dozens of models. However, the functionality of the Shiva vastly surpasses that of today's assistants. The Shiva replaces cell phones, pagers, personal recorders, notepads, and calendars. In addition, the Shiva adds video and network capability providing instant access to any information desirable, regardless of time or location. As part of the original intent, the Shiva will provide entertainment resources as well, such as interactive books. Patents have already been granted on designs for a type of reconfigurable interactive book [28]. Technology that will produce automatic summaries and abstracts of books and documents with an adjustable degree of condensation are projected for the year 2009 [6]. Eventually language translation will be available in such units, predicted for practical application in the year 2013 [6]. A variety of designs from compact, to book-sized Shivas have been planned. Some of these are shown in Fig. 1.7.3.

Data zones are repositories of localized information with standardized interfaces. Originally they were conceived as information hubs where maps and local community information, such as restaurant and entertainment information, might be accessible to people entering the zone. A physical port exists where information can be downloaded or uploaded from devices such as magic pens and the Shiva. In the workplace, a data zone might contain process information, product information, diagrams, and control information—both historical and real-time. There is a plethora of information that might be stored in a localized zone useful for the industrial engineer, including work orders, schedules, productivity rates, efficiency rates, current work assignments, a log of visitors in the zone, daily notices, safety regulations, and other location-specific information. Widespread use of integrated information wiring and standard plug sockets or interfaces for information services are projected to be in the home and office by the year 2007.

One of the hottest consumer products on the streets of Japan in 1998 was a device best described as the "love getty." This is a small transmitter/receiver worn by a person (typically a teenager) for indirect communication with others. A typical use is to select a preprogrammed request, such as "I am looking for a friend." When someone within a limited zone passes by who is also looking for the same with their device, the two love gettys sound an alarm, which enables the two to find each other, like a homing device. This is a primitive form of Philips's perception of hot badges, which could be coded with any sort of personal information desirable. The information could be made accessible to the public or to select groups. Naturally the badges could be used for personal want ads, but they might also be encoded with relevant work-related information. Information such as personal qualifications, certifications, and experience might be made available. Hot badges may be used as passes to certain work areas for location of other workers. Similar to the love getty, one might input a request such as "looking for quality supervisor." Linking hot badges to products and processes might be used as historical data tracking devices. These devices could radically change the nature of work measurement studies. Hot badges might also be linked with data zones. It is conceivable that each person may own quite a variety of these hot badges. Some conceptual designs for hot badges are shown in Fig. 1.7.4.

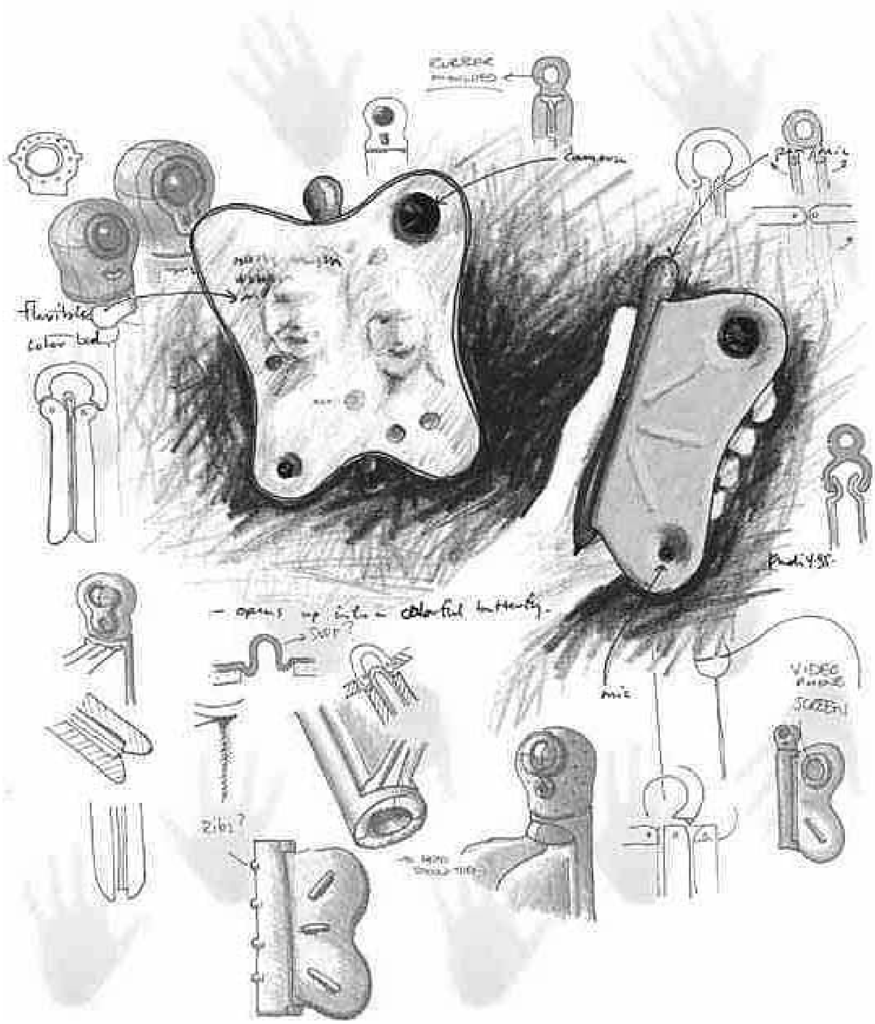


FIGURE 1.7.3 Conception of the Shiva. *(From the Vision of the Future Project conducted by Philips Design, Eindhoven, The Netherlands. Used with permission.)*

These are a few of the conceptual future products that will be available. Many other products are planned for which work-related application might become apparent. Designs have been made for video phone watches, certain to be on the holiday gift list of many a child. Interactive jewelry has been designed to be used for more personal communication, vision enhancement (allowing the viewer to see better than 20/20), hearing enhancement (permitting audition well beyond the norm or filtering unwanted frequencies), and enhanced smelling. These devices could benefit safety and improve worker perception for a variety of tasks. Digital makeup boxes are conceived to morph and change personal appearance for digital video communication—for those times when we want to look or sound better than we do. Who knows what eventual uses there will be for Philips's body scanners?

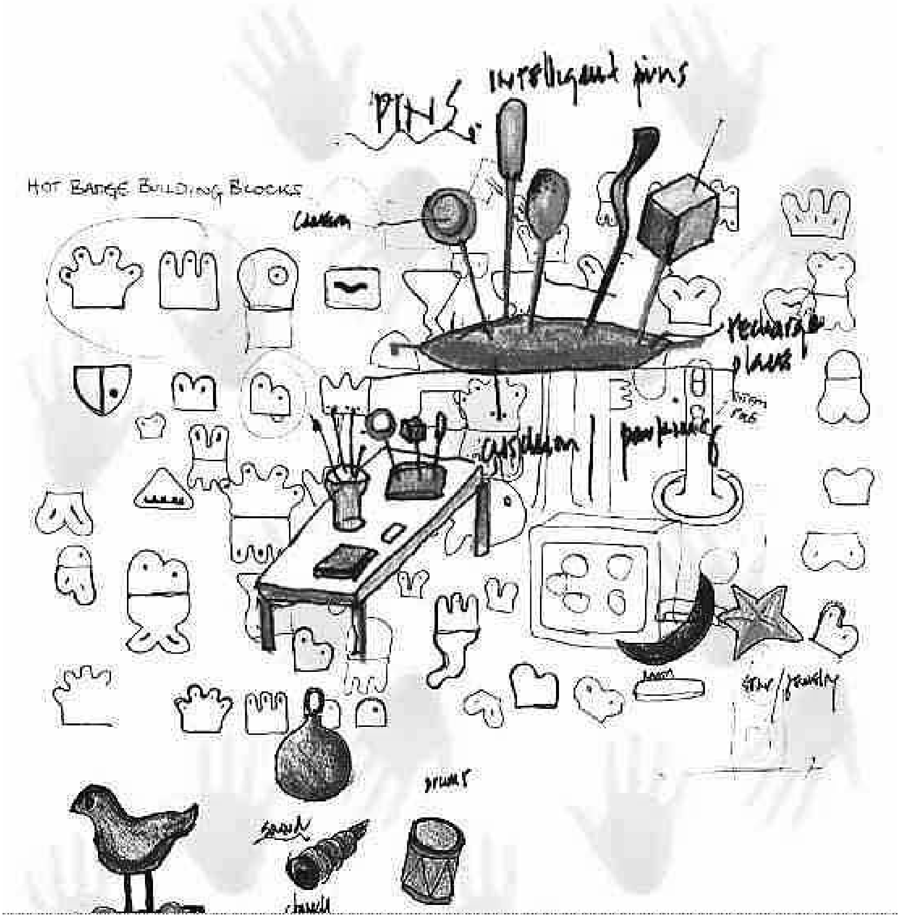


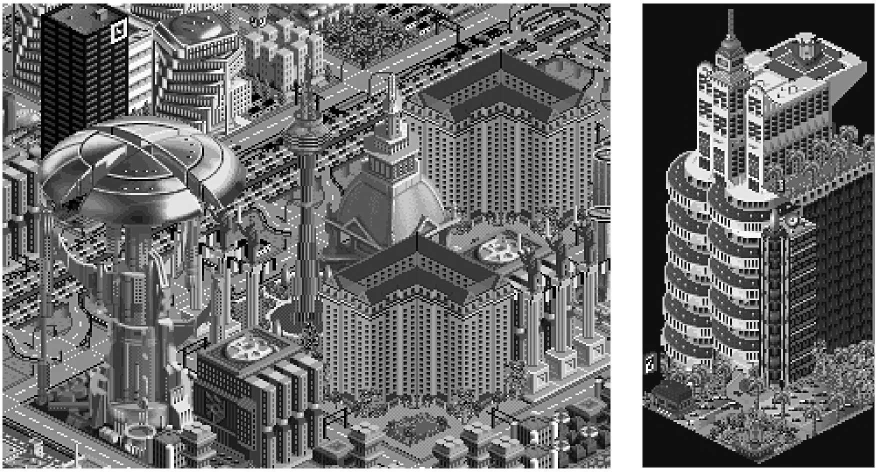
FIGURE 1.7.4 Conception of hot badges. *(From the Vision of the Future Project conducted by Philips Design, Eindhoven, The Netherlands. Used with permission.)*

SIMULATION TECHNOLOGY

Simulation and Entertainment

One outcome of the dramatic advances in information technology will be in the area of computer simulation. Computer simulation has long been an important tool used by industrial engineers to solve a variety of problems. Several predominate, discrete event simulation languages used today were developed in the industrial engineering community. However, many relatively complex and fascinating simulation systems have been developed for the entertainment industry in the form of games. One such game is designed to simulate cities.

Starting with a barren region of land and a set of building icons, the city simulation environments permit a user to build and simulate large-scale cities, such as the one depicted in Fig. 1.7.5*a*. The model building environment includes housing zones, industrial zones, commercial zones, airports, stadiums, power generation utilities, electrical grids, plumbing,



(a) (b)

FIGURE 1.7.5 Game-based simulation of cities. *(Courtesy of Les Freeman.)*

police stations, fire stations, roads, and more. The user must strategically build the city with concern for the building rate, location of model elements, established tax rates, distribution of tax to services, and model integration. The simulation determines, among other elements, growth behaviors, crime, traffic, economy, and natural disasters. Feedback comes in visual form at macro- and zoomed-in microlevels and through simulated newspaper reports of public concerns. There are infinite city possibilities and numerous web pages devoted to different versions of the game, including multiplayer Web-based simulations. The simulation environment is sufficiently flexible to allow users to modify and import city elements and graphics, as shown in Fig. 1.7.5*b*. Several features of the city simulation game and other simulation gaming environments promise to become tools for modeling and analyzing complex systems. Of particular interest is the ability to model at multiple levels where model elements have their own behaviors and interact with the integrated elements to create a complex system.

Casti characterizes a *complex system* as a system having at least a medium-sized number of adaptive intelligent agents that interact on the basis of localized information [29]. Examples of complex systems that have been historically simulated include weather systems, planetary systems, and molecular systems. A factory system could likewise be considered a complex system depending on the degree of factory characterization. At a machine level it might be desirable to create a process simulation for control and machine monitoring. Another level might be the product flow level for analyzing scheduling and inventory policies. A higher level could be an enterprise simulation for analyzing information flow and strategic policy making. At each level there are entities, or agents, that have their own localized behaviors, which are not dependent on the larger system. Other complex systems could include hospital, health care, environmental, distribution, military, and city management systems. Simulation is an attempt to capture a portion of the real world in a computer. With advances in computation and communication technologies, we are approaching an ability to perform computer experimentation on multilevel complexity systems. These advances have "finally provided us with computation capabilities allowing us to realistically hope to capture enough of the real world inside our programs to make these experiments meaningful" [29].

Object-Oriented Simulation

Over the past two decades there has been a phenomenal growth in the research and development of object-oriented simulation (OOS) tools and techniques. Some of the major application areas for simulation include communication systems, dynamic systems, electric power systems, military systems, environments and ecosystems, and discrete parts manufacturing. Some highly specialized commercial OOS environments have been developed in nontraditional areas, including multimedia graphics simulation [30] and distributed interactive simulation environments for building large-scale multiplayer 3D applications [31].

Object-oriented programming is marked by language characteristics that make the simulation modeling process fundamentally different from conventional simulation modeling. A primary modeling distinction is in the way the modeler views and constructs a system model. OOS tools provide the modeler with the ability to develop simulations using entities that are natural to the system [32], appeal to human cognition, and exhibit localized behaviors, which is important for complex systems. These entities, called *objects,* also have been identified as promoting faster model development, easier maintenance, enhanced modifiability, reuse of software and designs, and evolvability [33, 34].

In most traditional simulation languages, the modeler is constrained by predefined modeling constructs or entities. When simulation modeling needs vary from the constructs, the modeler must resort to writing custom programs. A fundamental difference with OOS is the inability to define, combine, expand, and reuse small self-contained programmed units through classes, which are generic templates for the objects. Objects that have natural physical boundaries are often the result of these capabilities. For example, suppose that a modeler wanted to simulate a traffic system. Natural modeling objects might include cars, pedestrians, roads, sensors, and traffic signals. Perhaps the modeler wanted to differentiate trucks from cars. An OOS environment would typically allow the modeler to make a new truck object by adding to the car object. These objects would contain local data desired by the modeler, such as the car's current location, speed, direction, number of passengers, and/or appearance. This is the feature that permits users to modify the appearance of the city simulation game objects. Modelers can create their own object descriptions and input them into the objects' local variables, as was shown in Fig. 1.7.5*b*. The objects can also be programmed to contain the objects' local behavior, typically based on rules. For example, when the car object arrives at a yellow signal object it would then reduce speed. Behaviors for stopping, starting, accelerating, turning, and many others can be given to the objects. In the simulation model, objects can be created, placed in the system, and allowed to operate independently using their set of behaviors, such as in the city simulation game. The primary issue is flexibility in modeling. Any simulation language will exhibit modeling barriers without the capability of creating entirely new modeling entities and providing these entities with their own behaviors.

There are two primary underlying mechanisms in OOS that provide these modeling advantages. They are *polymorphism* and *dynamic binding.* Polymorphic languages have values or variables that may have more than one type. Operands or parameters in polymorphic functions can have more than one type. Dynamic binding is the mechanism that creates a reference for polymorphic behavior that allows new objects to be created and interfaced with an existing implementation without affecting the existing code [35].

There are some disadvantages to OOS, however. Model development time is reduced for the programmer who has a developed set of class (object) libraries. However, for the simulationist experienced in conventional tools, the learning curve and the object development time might be formidable. However, model development time for the experienced object-oriented programmer may even be longer than conventional approaches if the classes must be developed first. For this reason future domain-specific OOS environments developed with their particular set of class libraries will emerge. There are several general-purpose OOS languages available as well as many domain-specific OOS environments.

General-purpose OOS languages typically have class libraries available for the simulation engine and facilities for building other classes. OOS can be built using general-purpose object-oriented (OO) languages such as C++, Smalltalk, CLOS, or JAVA, which do not typically come with standard simulation class libraries. OOS general-purpose languages include rich sets of simulation class libraries and interfaces for development of simulation models. Robust OOS languages include Simple++, MODSIM III, G2, and VSE. Two unique OOS languages are Silk [36] and Simjava [37], which are intended for simulation across the Internet. Simulation across the Internet will permit modelers to integrate and link multiple model levels and house objects in remote locations. Internet simulations have already been developed that permit virtual teams to interact. An example of this is the Virtual Factory Teaching System that is used to build factories, forecast demand for products, plan production, and establish release rules for new work into the factory [38]. Fully distributed Internet simulation may be common within 5 to 10 years.

Many domain-specific OOS environments have also been developed with extensive class libraries. Several of these are listed in Table 1.7.2. In the area of discrete event manufacturing simulation there are several OOS research platforms currently under investigation including BLOCS/M [39], SmartSim [40], AGVTalk [41], CAD/MHS [42], and OSU-CIM [43]. A good review of these environments can be found in Ref. 44. Other research in OOS is addressing standards for object interaction across the Internet [45], intelligent agent objects that are capable of independent existence [46], and object-oriented architectures for speed enhancement [47].

In the next 5 to 10 years there will be an emergence of many more domain-specific simulation environments and objects. It has been predicted that separation of developed software into components, and use of software libraries, which facilitate the reutilization of those components, will be widespread by the year 2006. The fundamental characteristics of OOS make it particularly well suited for larger, more complex, distributed simulation, and Internet-based simulation. Many of these new environments will be commercial, but an even greater number of the simulation environments developed will be owned by individual organizations.

VIRTUAL REALITY

Virtual Reality Background

The area of virtual reality (VR) has captivated a diversity of constituents, from researchers and futurists to the general public. Perhaps there is no other area that has the potential of fundamentally changing the way we live and work. As we move toward the year 2010, the explosion of information technology coupled with the advancements in simulation will change the way we learn, the way we model, the way we analyze, and the way we communicate. In this section we will look at VR technologies and research. While a general overview of the area will be presented, the focus will be on VR for manufacturing and education. Some specific examples for vir-

TABLE 1.7.2 Examples of Domain-Specific Object-Oriented Simulation Environments

Simulation name	Application area
Numerical Propulsion Simulation System (NASA)	Modeling and simulation of arbitrary engines.
National Micro-population Simulation Resource	Study of structured populations for biomedical research such as epidemiology, genetics, and demography
Nuero solutions	Neural network modeling and simulation
Silux	Modeling and analysis of dynamics of large mechanical systems
Taylor ED	Production flow business process optimization
PARADISE	3-D graphical modeler for creating simulation games
Rapid+	Prototyping of electronic products statecharts

tual manufacturing will be discussed, and we will also provide a look beyond the year 2010 from the Japanese technology forecasts for the year 2025.

Ellis defines virtualization as "the process by which a human viewer interprets a patterned sensory impression to be an extended object in an environment other than that in which it physically exists" [48]. Research in VR is progressively moving to combine a complete range of human sensory experience into a single simulated environment. VR had its beginning in the late 1950s and early 1960s, both in the artificial intelligence and entertainment fields.

In the field of artificial intelligence, the emphasis has been on efficiency of technology and the formal process where speed, resolution, and interface must all be considered. One of the early precursors to VR came from the thesis work of Ivan Sutherland in an implementation called Sketchpad. Sketchpad was a methodology for creating graphical images from abstract concepts. Extensions of the concepts in Sketchpad led to what many consider the origins of virtual environments. In the early 1960s, Sutherland developed head-mounted stereo displays for engineering applications, which ultimately led to the development of vehicle simulators, particularly aircraft simulators.

The entertainment field has focused on the artistic side of VR, hoping to create a human experience. One of the first developed technologies was called *sensorama,* which was developed and patented in 1962 by Morton Heilig. The intent of sensorama was to provide a sensory experience of a motorcycle ride by combining visual, audio, motion, and smell experiences. With Heilig's sensorama, a person would sit on a specially equipped motorcycle wearing a headset for viewing and experience a ride through the streets of New York or through the sand dunes of California. Throughout the ride the sensation of breezes and authentic smells were also provided.

A myriad of VR applications has grown from these beginnings. Today applications have been developed in many fields, including medical imaging, architecture, augmented reality, education and training, games and entertainment, human modeling and animation, manufacturing, and wearable computing. Development and interaction in these virtual environments is achieved through the use of various visualization and data capture devices, often referred to as *immersion technologies.*

Head-mounted displays (HMD) are a type of immersion technology that facilitates visual imaging. Coupled with software, these displays often provide panoramic visualization including 3D viewing. Many HMD look like goggles, combining sensing technology to monitor head movements. Efforts are under way to reduce the size of these displays. Monocular displays are designed for one eye and permit the wearer to see virtual images superimposed upon the real world, allowing the user to see through the virtual image. Shutter glasses operate by synchronously blocking the view of left then right eyes while displaying the computer image onto the alternating eye views. Using this technique, shutter glasses provide a stereoscopic view. A project called VRD is based on the concept of scanning an image directly on the retina of the viewer's eye, which will produce a full color, wide field-of-view, high resolution, stereo display in a package the size of conventional eyeglasses. In the future, these displays may appear as virtual see-through displays on eyeglasses or even possibly on something as small as contact lenses. For industrial engineers, these tools could be used to view concepts or simulations within or overlaid on the physical environment, such as a modification to facilities or the addition of new a subsystem. Systems integration will become a visual on-site process, both in the planning and implementation phases.

Similar to HMDs are data capture devices that track the movement of the eye—useful for object and computer interaction without hands. Other data capture devices include data gloves that record the position of the hand and arm for interaction with the computer. Massachusetts Institute of Technology (MIT) laboratories recently developed a data capture and interaction device called the PHANToM [49], which provides users with the illusion of touching virtual objects. There are also technologies for capturing complete body position and motion for unconstrained interaction with virtual objects [50]. Most of these data capture and interaction devices are still constraining and have limitations. By the year 2010 data capture and virtual object interaction will be unconstrained. These devices will consist of small, mostly wireless, modules that will permit the user to participate in a complete sensory experience, beyond sensorama to a world of "experience-orama."

Virtual Reality Research

Numerous laboratories and universities are conducting VR research. While it is impossible to list them all, a few of them will be presented. A good beginning Web-based resource at the University of Washington provides an overview of activity in many VR domains [51]. One area of importance is the interaction and performance of people using VR equipment, such as displays and data capture devices. The Advanced Displays and Spatial Perception Laboratory, part of the NASA Ames Research Center, is investigating human interaction with a variety of displays (including intelligent displays) for air traffic control, teleoperation, and manufacturing [52–54]. Results of this work will help in the design and effective use of future VR immersion and data capture devices. Research in data capture is being conducted at Carnegie Mellon University (CMU) [54] where the DigitalEyes project has demonstrated a noninvasive, real-time tracking system. Complex articulated figures, such as the human body, are tracked in 3D and converted to digital images. Many projects are examining the mixing of real and virtual objects, sometimes called *augmented reality.* Another project at CMU is the Magic Eyes project. This project uses 3D tracking technology to augment reality. The system tracks known 3D objects and then superimposes the object with virtual information [55]. The Fraunhofer Project Group for Augmented Reality is developing technology for computer-aided surgery, repair, and maintenance of complex engines, facilities modification, and interior design where the user will interact with virtual objects [56].

Research is also being conducted to discover alternative forms of presenting virtual environments to the user. An alternative form of presentation could take place in larger enclosed areas, such as rooms, reminiscent of the holodeck from popular science fiction, where users do not need immersion eyewear. One such effort is the CAVE project of the Electronics Visualization Laboratory at the University of Illinois at Chicago. The CAVE is a room constructed from large screens on which graphics are projected onto three walls and the floor, and track the user in real time to provide a multisensory virtual experience [57]. Another intelligent room called HAL has been developed at MIT [58]. Other research is addressing VR interfaces. As the technology matures there will be a need for the development of new approaches for interacting with the data and with simulation. The National Center for Supercomputing Applications (NCSA) VR laboratory located in the Beckman Institute for Advanced Science and Technology on the University of Illinois campus is engaged in the exploration of new methods of visualizing and interfacing with scientific data and simulations. Their work facilitates the use of immersion technologies with representation, presentation, and interaction with many types of data. For some time industries have been interested in the development of sensors that can distinguish more abstract characteristics, such as smell and taste. In the future it may well be possible to provide data that can be felt, smelled, or even tasted.

At the Lawrence Berkeley National Labs, 3D modeling and VR are being explored as curriculum tools. With the development of The Frog, a user can dissect a frog by cutting and removing user-selected portions of the frog [59]. Ultimately the designers intend to "enter the heart and fly down the blood vessels," allowing users to poke their head out at any point to visualize anatomic structures. The Digital Brain, using similar technology, has been developed at the Harvard Medical School [60]. In this project, brain scans have been collected from real-life patients prior to brain surgery. Physicians then are able to perform virtual surgery to identify problems before the actual surgery. At the National Library of Medicine, the Virtual Human project is intended to create an entire human for medical training [61]. The concept of a virtual human is being researched by many other organizations as well.

In the early 1990s there was a short-lived science fiction serial starring an intelligent entity named Max that lived in a computer. Max was a fully dialog-capable "being" capable of moving about the Web and interacting with other computer programs as well as humans. One

FUTURE TECHNOLOGIES FOR THE INDUSTRIAL ENGINEER

might call Max a virtual human. The Computer Graphics Lab at the Swiss Federal Institute of Technology is developing technology for simulation of real-time virtual humans [62–64]. They model the physical entity and then apply behavioral motion based on physical laws. This includes models for walking, grasping, motion synchronization, collision detection, and virtual sensors like virtual vision, touch, and audition. Perhaps they are best known for their creation of virtual animated actors, such as a synthetic Marilyn Monroe. The number of organizations working on aspects of virtual humans is rapidly growing. The Virtual Humans Architecture Group is an effort to bring together the multiple groups working on virtual human projects and to develop standards for virtual humans [64]. A good list of such organizations can be found in the cited URL. One future use of virtual humans will be for simulations and studies conducted with facilities planning, where visualization of humans working with equipment will provide better predictions of production efficiencies prior to implementation. Virtual humans will likely be used to determine efficient work methods and to conduct ergonomic studies of work tasks. By the year 2007 it has been predicted that there will be practical use of electronic secretaries featuring information agents, voice recognition, and other functions [6], which could possibly make use of virtual humans. This will lead to an increasing use of intelligent assistants in many job-related functions as we approach and move beyond 2010.

Virtual Manufacturing

A growing interest in virtual manufacturing has resulted in conferences and symposia addressing the topic, such as the Virtual Reality in Manufacturing Research and Education symposium cosponsored by the National Science Foundation [65]. Virtual manufacturing issues include a perspective view of manufacturing layout and floor design, mechanical design, telemanufacturing, CAD/CAM (computer-aided design/computer-aided manufacturing), and agents in scheduling. Likewise a number of laboratories are working in this area. The VIS-Lab at the Fraunhofer Institute for Industrial Engineering is developing tools for assembly planning where users can assemble and disassemble products in open or restricted space [66]. The Concurrent Engineering Center of the Oak Ridge Centers for Manufacturing Technology has developed 3-D virtual factories with the goal of completely simulating the shop floor. They include simulation of material removal processes, experience human factor studies, and walk-throughs [67]. A number of organizations are working on virtual machining research. The Machine Tool—Agile Manufacturing Research Institute (MT-AMRI) has developed Virtual Machine Tool (VMT) software that is capable of simulating and evaluating different machine topologies and configurations [68]. Similar work has been conducted by Paul Wright with extensions to network-based machining with a tool called Cybercut [69]. And there are many other organizations producing similar results. The National Institute of Science and Technology Policy of the Science and Technology Agency of Japan has conducted technology-forecast surveys every five years since 1971. The latest survey, published in 1997, used Delphi techniques involving over 4000 experts [6]; see also Ref. [70]. The results specified over 1000 specific technology forecasts in a variety of areas. Table 1.7.3 depicts a summary of some of these forecasts that have particular relevance to manufacturing. Most of these advances are predicated on advances in information technology, simulation, and virtual manufacturing.

As early as 2005 there will be information management systems operating between companies (item 1), which will require standards and translation capability as is being addressed in the STEP (standard for exchange of product model data) standard. Virtual reality is predicted to begin to play a significant role by 2006 integrating human and virtual objects in interfaces with production equipment (item 2). Advances in computer-integrated manufacturing (CIM) are predicted to significantly reduce manufacturing costs in some sectors by 2006 (item 3). These advances should be influenced by the development of virtual factory models and simulation. However, complete automation of the production process directly from the design is not projected to take place until around 2010 (item 10). Standards in communication between manufacturing suppliers and distributors are predicted to lead to wide-

TABLE 1.7.3 Japanese Government Technology Forecast for Selected Manufacturing Technologies

#	Predicted manufacturing technology advancement	Year
1	Widespread use of systems to unitarily handle information management (orders, design, manufacturing, maintenance) among related companies	2005
2	Radical changes to the production and machinery area through multimedia technology through interface between the analog world of human perception, characterized by visual and auditory senses, and the digital world of computers and other digitally operated artificial objects	2006
3	Practical use of CIM for shipbuilding, which incorporates design/production databases and intelligent CAD/CAM systems, leading to a reduction in shipbuilding labor costs to half the present level	2006
4	Strengthening the relationship between consumption and production and advancements in networking between stores and factories, leading to widespread mergers between manufacturers and retailers/wholesalers and between manufacturers and distributors	2007
5	Practical use and an electronic secretary that features information agents, voice recognition, and other functions	2007
6	Widespread use of paperless processing for the majority of office work	2007
7	Practical use of superprecision processing technologies (machining, analysis, and measurement to testing) through the availability of length, displacement, and surface roughness to the angstrom level and time order to the femtosecond order	2009
8	Achievement of 90% recyclability for motor vehicle parts and materials	2009
9	Development of maintenance robots capable of diagnosing and repairing machinery and equipment	2009
10	Automation of most machining process designing jobs based on artificial intelligence techniques, leading to widespread use of technologies for directly machining from design data	2010
11	Development of diagnostic technologies, which enable in situ estimation of remaining life of metallic materials structures and components depending on service conditions, by nondestructive inspection for fatigue	2010
12	Discovery of new laws, effects, and phenomena through microtechniques, leading to a radical change in the theories of designing artificial objects	2011
13	Widespread use of robots for hazardous work or extreme conditions	2011
14	Widespread use of voice-activated word processors that support continuous speech by unspecified persons	2011
15	Widespread use of designing, producing, collecting, and recycling systems that make it possible to recycle most used materials through legally establishing manufacturers' responsibilities for collection and disposal of disused products	2012
16	Practical use of pocket-sized voice-actuated interpreting machines that allow people to communicate even though they do not speak each other's language	2012
17	Widespread use of production systems that provide comprehensive support for senior citizens and people with disabilities experiencing functional degeneration	2013
18	Practical use of intelligent robots with visual, auditory, and other types of sensors, capable of judging their environment and making decisions	2014

spread mergers by 2007, again aided by virtual factory models. Early versions of virtual humans in the office place may begin with electronic secretaries (item 5). Intelligent agents will combine with virtual reality to make it possible for senior citizens and people who are physically or mentally impaired to routinely use production equipment (item 17).

Environmental concerns are predicted to significantly increase recyclability (item 8) and eventually lead to integrated design, production, and disposal systems enforced by law (item

15). Paperless workplaces have long been predicted; perhaps it will become reality in 2007. But we will have to wait until 2011 for voice-activated word processors (item 14). In 2012 it is predicted that there will be no language barriers in the workplace because of automated translation units (item 16). Likewise, robotics will continue to play an important role in manufacturing as a result of virtual and simulation processes. Robots eventually may diagnose, repair, perform hazardous work, and be equipped with advanced humanlike sensors that will aid them in making intelligent decisions (items 9, 13, and 18).

CONCLUSIONS

Predicting the future has many purposes. In this chapter a survey of future predictions in the areas of information technology, simulation, and virtual reality has been addressed. For the most part these projections have come from experts in industry, academia, and government. Some of these projections are probably optimistic and some of the advancements will occur faster than projected. For many of the predicted advancements to take place there will need to be a corresponding advancement in theory. Theoretical advancements are, however, hard to predict. Regardless of the pace at which these technological advances occur, some general observations can be made:

Information technology will advance.

Computers will get faster and memory will become more plentiful and economical.

Satellite technology will give us the ability to communicate from anyplace on the globe.

The Internet will continue to grow and we will eventually experience incredible connection speeds.

Simulation combined with virtual reality will become an increasingly valuable modeling and analysis tool.

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BIOGRAPHY

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CHAPTER 1.8

THE FUTURE DIRECTIONS OF INDUSTRIAL ENTERPRISES

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This chapter summarizes several influential industry-led studies that over the past several years have identified new directions of development and prioritized road maps and action plans for infrastructure to support the industrial enterprise. Companies are moving from stand-alone entities that pass product one to another, to links in an interactive, adaptive, extended enterprise that deal successfully with rapid change. To do so requires an unprecedented level of integration of people, business processes, and technology.

Within this overall context, the chapter will discuss the key enabling systems necessary to implement the evolving directions of the industrial enterprise. These systems relate to people and knowledge, business processes and technology, and integration of these into an effective, globally competitive, coordinated system.

Implementation of the enabling systems leads to interesting dilemmas for executives and other workers. The implications, and what to do about them, are discussed.

THE STRUCTURE OF THIS CHAPTER

Irresistible forces are pulling industrial enterprises in new directions. The explosive growth of communications, technology, and education, allied to the globalization of markets, is changing both the structure and strategies of companies. The new drivers of the industrial economy require new company characteristics, which in turn require the introduction of various enabling systems, which in turn lead to new management problems. This chapter covers these subjects in that sequence, namely

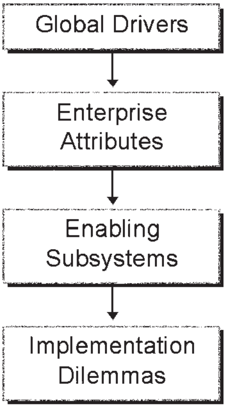

FIGURE 1.8.1 Flow of this chapter.

1. The drivers of change
2. The attributes or characteristics of companies that compete successfully in a world defined by those drivers
3. The enabling systems that allow a company to attain those attributes
4. The management and other problems one encounters when implementing the enabling systems

The material is taken from two industry-led studies in the United States that dealt with these issues and summarized and analyzed many previous reports and books. These are publicly available (see reference list at the end of the chapter) as the 1991 report, *21st Century Manufacturing Enterprise Strategy* [3], and the 1997 report, *Next-Generation Manufacturing* [4]. Figure 1.8.1 illustrates the main topics that this chapter will examine.

DRIVERS OF THE NEW INDUSTRIAL STRUCTURE

It is a mistake to think the global drivers of change do not affect your company. It may operate locally and feel confident that it is giving good value to its customers, and it may feel that worldwide changes are not on its horizon. However, even if your company does not operate in global markets, global competitors will come to your company's local market. The changes sweeping the world's industrial and economic structure will soon be seen in everyone's competitive arena. Your company may not go out to the world, but the world will be coming to its backyard. This is being pulled into place by irresistible economic forces, against which even government regulation is a short-term stopgap.

The factors that are coming together to create a new industrial structure are described in the following section. Note that these are mutually reinforcing items. Developments in one item catalyze further advances in others. The factors are

- *The ubiquitous availability of information.* With a global communications network now a reality, it is possible to transmit and receive all types of information everywhere. Virtually everyone on every part of the planet can know how others are living. As a result, the constant human striving for greater standards of living is accelerating. This flood of information creates a new challenge for manufacturing enterprises. Since useful information is now universally available, competitive advantage has shifted from the ability to distribute information to the ability to filter and act on the information. This becomes a strong driver of both information systems technology development and of the knowledge and training requirements of the industrial workforce.
- *The spread of technological education around the world.* Technological education is spreading rapidly, fed by the information revolution. Educated people take advantage of that information revolution in their work processes in order to compete globally. The ability to design and manufacture products is becoming more widespread. Even in those countries considered less developed, there are groups of people with a high level of technological education that are able and very keen to make modern, quality products. Education and the ability to apply knowledge to use information are becoming the competitive differentiators, and these are enabling many countries and communities to join the ranks of effective manufacturing competitors.
- *The decreasing cost of individual production machines and design aids, with the increasing cost and complexity of systems.* The production capability, which cost U.S. $1,000,000 a decade ago,

is now available for one tenth of that cost. The capability of computer-aided design (CAD) packages that cost U.S. $50,000 a decade ago is now available in packages costing U.S. $1,000. As a result, many companies, including small ones, now have access to tools of industrial competition that were denied to them before. On the other hand, the complexity and cost of major production systems, such as fabrication facilities for semiconductor chips, rises from generation to generation. For chip production, the cost of a fabrication plant is approaching U.S. $2 billion.

There are more types of participants in the industrial food chain and more players for each type. The kinds of competitors are more varied than before, from large multinationals with access to capital, to small groups of technically savvy and highly motivated individuals far away from their customers geographically, but connected interactively by modern communication technologies.

- *The relentlessly accelerating rate of technological innovation, which is applied to product and production process alike.* As our understanding of technology becomes greater, fueled by the spread of communication and education, new developments come faster, leading to near-exponential growth of ideas, inventions, and products. The explosion of technical knowledge in turn drives an increasing complexity and interdependency in manufacturing enterprises as more and more knowledge is required to fulfill customer expectations. Just as agriculture, through innovation and productivity, has increased its output with a smaller labor force over the past decades, traditional manufacturing labor in the United States is projected to decrease by about a million jobs over the next 10 years. On the other hand, new jobs are being created and new skills needed, especially to deal with the enabling systems outlined in this chapter. It is not clear that the quantity of new jobs will match the quantity of those being lost, but it is clear that competitive pressures will not allow any company or community to avoid this evolution.
- *The emergence of ecology and environmental considerations as forces in society.* Global development is increasing pressure on the environment and heightening tensions over world resource utilization. The United States, with about 7 percent of the world's population, consumes a disproportionate share of the world's resources; the developed countries, with 15 percent of the world's population, consume 50 percent of the world's energy. As the developing nations increase their resource consumption, more efficient use of resources will become essential to global survival.

  The driver is not environmental regulation, but the widespread societal appreciation of this problem. The importance of strategies to minimize resource use, maximize reuse, and apply environmentally conscious materials and processes in both products and manufacturing systems will continue to grow. Best practices of recycling and conservation, applied to all business functions and forms of resources, will become an accepted part of industrial practice, regardless of where the operations are located.

THE ATTRIBUTES OF THE MODERN MANUFACTURING ENTERPRISE

Leading manufacturers by the late 1990s had assimilated good practices such as focusing on customers, managing for total quality, becoming lean by eliminating wasted time and material, complying with environmental regulations, and becoming a learning and teaming organization. As more and more companies successfully adopt them, these practices are less helpful as competitive differentiators. Being a successful competitor when faced with the new drivers mentioned in the previous section requires additional attributes.

In the days of mass production, the aim of a manufacturer was to make timely, high-quality, reasonably priced product. The customer ordered from a catalog and the product's properties were determined by the manufacturer, who may or may not have spent time consulting with customers. People in the organization were consumed with shipping product, and this pressure was especially felt at the end of a quarter when the financial statements were closed.

The explosive growth of real-time information exchange between companies, together with multicompany teaming and global multiventuring, changed the focus of the manufacturer. Manufacturers used to be stand-alone operational entities, passing product from one to another. The real-time exchange of information has now created a situation where the work processes in one company affect other companies, immediately. The old-fashioned business environment in which each company could be managed in isolation has changed into one in which decisions made by one business directly impact decisions in other businesses. Management today involves continuous interactivity between businesses. The context within which a manufacturing company works is the *extended enterprise.* In this emerging dynamic system, the link in the chain, which is the individual enterprise, has moved from being an arm's length entity to becoming interactive and often international, functioning in the world of the Internet. The name *interprise* is gradually coming into use for such an interactive enterprise.

The interactivity between companies has placed emphasis on the concept of the extended enterprise. It is important to clarify the distinction between a company and an extended enterprise:

- A *company* is a conventionally defined, profit-making entity with management sovereignty and well-established bounds of ownership and liability. It is charged with responsibility and control over its own actions and is liable by law.
- An *extended enterprise* is a group of companies (and possibly other institutions) that develop linkages, share knowledge and resources, and collaborate to create a product and/or service. This collaboration maximizes combined capabilities and allows each institution to realize its goals by providing integrated solutions to each customer's needs.

The ability to speedily make and supply high-quality and reasonably priced product is found around the world, including in countries where intelligent knowledge workers are happy to earn relatively low wages. The aim of a successful manufacturer goes beyond making product; it is to *become part of its customer's lifestyle or business processes.* The good product is taken for granted. The CEO of IBM, Lou Gerstner, said, "The number one thing that will drive IBM's growth in the future is a total commitment to solutions, not piece parts. We're not selling a browser. We're not selling a 3D engine for your PC. We're selling ways for companies to make more money." Hundreds, probably thousands, of manufacturing companies are adopting the same philosophy.

The 1997 Next-Generation Manufacturing (NGM) project identified the six attributes mentioned in the following list. These are similar to the attributes identified in the 1991 report, *21st Century Manufacturing Enterprise Strategy,* which recognized the emergence of the new competitive framework called *agility,* and both will be discussed here. While some companies practice some elements of these attributes, none practices all. The attributes should be thought of as a compass, giving a direction. Whatever the attribute, a company can do more of it. As companies continually improve their posture with respect to the attributes, they will come closer to achieving next-generation capability.

The six attributes identified by the NGM study are

1. Customer responsiveness
2. Physical plant and equipment responsiveness
3. Human resource responsiveness
4. Global market responsiveness
5. Teaming as a core competency
6. Responsive practices and cultures

Customer Responsiveness

Customer responsiveness means much more than asking the customer what he or she wants and fulfilling that request. The future industrial company will work with and in anticipation of customers to supply an integrated set of products and services that provide solutions to fit evolving life cycle requirements of function, cost, and timeliness.

To truly anticipate needs and keep them evolving, an intimate relationship between manufacturer and customer is necessary, whether the customer is next door or in a different country. This informed anticipation goes beyond learning customer needs only from reaction to prior products, but proactively digs for needs about which even the customer is too uninformed to articulate. The General Motors vice president for consumer development, after accounting not just for cars purchased and services rendered but also for income from auto loan financing, figures that a loyal customer is worth U.S. $400,000 over a lifetime.

By concentrating on total customer needs, the value of integrated packages of products and services can be exploited to provide the customer with a total solution that is highly valued. Rather than viewing customers as a source of income in single transactions, a longer-term partnership is established, which generates a revenue stream that spans the life of the customer relationship.

Physical Plant and Equipment Responsiveness

Responsiveness goes beyond flexibly making any one of a given mix of products. The future industrial company will use an ever-growing knowledge base of manufacturing science to implement reconfigurable, scalable, cost-effective manufacturing processes, equipment, and plants that can be rapidly adapted to specific production needs.

The usual method for transfer of experience about manufacturing processes is by energetic and motivated individuals. That is too slow and inefficient for modern needs. The rapidly changing environment of manufacturing requires systematic procedures to increase knowledge of manufacturing processes available to companies. This is necessary not only for better quality and productivity, but to develop the faster and more innovative new processes that are needed.

Physical processes should be the fastest link in the value-adding chain. This is achieved by accruing greater fundamental knowledge and deploying enabling technologies while viewing and managing the whole extended enterprise system, which provides the solution to the customer.

Attainment of variable capacity is not solved by outsourcing to simply transfer the problem to a vendor. Instead, it requires innovations in hardware, such as flexible processes, and innovations in management of plant and equipment. For example, one manufacturing company leases production equipment only after getting an order—thereby matching product, product lifetime, and equipment. When the order is filled, the leases are terminated. This procedure has been common for decades in the construction industry. In the future manufacturing enterprise, the missions of specific facilities will change more rapidly, and the need to reuse or recycle equipment, plant, and even property will be more frequent. Designers of equipment and factories can no longer assume single missions and long lifetimes but instead think of the entire manufacturing complex as a recyclable entity that should be rapidly and economically adapted to new uses.

Human Resource Responsiveness

Traditionally, tasks at work were thought of as static and unchanging, and it was thought to be the employer's problem to train the worker, if training was needed. Today, adaptability of employees and training is always needed. The core workforce of the future industrial company will consist of highly capable and motivated knowledge workers who can thrive in a flexible work environment, with substantial, independent decision making.

If the watchword of yesterday was lifetime *employment,* the watchword now is lifetime *employability.* The responsibility that the worker be employable over his or her lifetime is becoming a joint responsibility. For example, to improve the employability of its members, the United

Steelworkers of America Union (AFL-CIO), together with more than 12 steel companies, has established the Institute for Career Development, Inc. in Mayville, Indiana, to provide college education for all their members.

Central to this attribute is the required ability of all individuals to develop and evolve a set of skills that make them true knowledge workers who remain valuable to the enterprise and continuously employable anywhere in their industry.

This will require a change in the implicit social contract that has existed in many large firms. De facto lifetime employment, which leads to task-specific training, will be replaced by overall employee knowledge development. In the next generation, this responsibility will be shared, but guided by the individuals as they enhance their skill set and prepare to work for several employers rather than just one or two. Continuous change will require concomitant continuous learning, leading to the establishment of a lifelong educational system.

Many U.S. firms have instituted education policies aimed at increasing the overall knowledge of their workforce. Motorola has a stated goal of increasing their training effort to 7 percent of payroll budget per year (around 1 month/year). Motorola acknowledges that this will increase the value of the employee, but it also may mean greater turnover as the employee becomes attractive to other companies. Motorola recognizes the advantage, which is to have knowledgeable workers, and the disadvantage, which is to spend money educating people who could end up with competitors, but aims to have capable alumni with pleasant memories of Motorola in companies elsewhere.

The knowledge of the workforce and the ability of a company to use that knowledge will become a distinguishing competitive factor. When asked, most executives report that only 5 to 10 percent of their employees' time is spent in creative and profitable thinking. This implies that there is an enormous resource of knowledge available to be tapped.

Global Market Responsiveness

As mentioned before, either a company will enter the global competitive market, or a global competitor will come to the company's market. Globalization cannot be avoided. What is left is to plan how to deal with this. The future industrial company will develop a manufacturing strategy to anticipate and respond to a continuously changing global market with its operations and infrastructure tailored to local requirements.

Although many companies have had international operations for decades, few are truly global companies. The steps toward globalization begin with offshore marketing, followed by centralized, offshore production for distributed worldwide markets, then as the local economy develops, global production becomes distributed. Not every company is large enough to go through all those stages, and some go no farther than an intermediate stage. For larger companies, local operations become indistinguishable from an indigenous company.

This global company will place any or all of its functions, including research and development, in whatever location is most advantageous. Such local operation is far more responsive than one centralized in the home country. As one CEO of a high-tech firm put it, "We use local design engineers because they best know the needs of the equipment and of the local markets." Caterpillar designs all of its small excavators in Japan because the requirements there are the most demanding for that product. Understanding local markets, cultures, and politics is essential to the responsive, global company. Accommodation of local customers and other stakeholders, serving local community and employee needs, may be more dominant factors in siting of plants and operations than traditional drivers such as low labor costs, transient tax advantages, or less stringent environmental regulations.

Teaming as a Core Competency

The traditional practice of hierarchic control is much too slow for the needs of the future enterprise, and inhibits release of the creative knowledge of a motivated worker. The industrial company will practice teaming and partnering within and outside the company to bring needed knowledge and capabilities rapidly to bear on development, delivery, and support of its customers and markets.

The accelerating increase in demands of the market makes it impractical for a company to respond with internal resources and new hiring. As teaming and partnering for access to both core and noncore competencies become key capabilities, workers and managers need to personally understand how to rapidly form, operate, and then disband a team. The company as a whole needs to enhance and retain its reputation as an honest and trustworthy entity with whom other companies will want to partner. Trust becomes a central issue, not for altruistic feel-good reasons, but for hard-nosed business reasons.

Successful modern manufacturers such as Nucor Steel, Solectron, Silicon Graphics, and service companies such as Southwest Airlines, for all of whom teaming is important, not only put emphasis on careful hiring, but tend to hire for attitude and train for skill. It is very clear that mid-twentieth century assumptions about how organizations function are no longer completely viable. The scope of hierarchy has eroded so that people share power: within small teams, task forces, and other groups, between corporations and institutions, and across borders and cultures. The challenge is to create a work environment that nurtures a deep level of commitment but is not based on old assumptions of lifetime employment.

Responsive Practices and Cultures

The attributes of the company are not static items to be built into the company and forever remain unchanged. The manufacturing company must constantly evolve. As Jack Welch, CEO of GE said, when the rate of change outside the company becomes faster than the rate of change inside the company, that company is doomed, however well it may be doing now. The future industrial company will have continuously evolving culture, organizational structure, core competencies, and business practices. These will enable it to anticipate and respond rapidly to changing market conditions and customer demands.

The ability to embrace rather than resist the new manufacturing environment is a question of culture. As a company increases productivity, it must grow revenue at a matching rate to avoid layoffs, or it must switch to new, higher-value activities that grow the business base commensurately. High margins come from new, high-value, total solutions, and these require innovation. The fundamentals of productivity are well understood and taught, but there are few codified fundamentals of innovation. Accordingly, the manufacturing company must teach both innovation and the process of change to enable this. It must not just have the answers, but also "live the question," always looking toward the next problem.

Diversity resulting from teaming and collaboration must be reflected in shared metrics. Cooperation is impossible if both partners continue to act based on conflicting functional or company-based metrics rather than on unified goals of the partnership. Unfamiliar values of other partners must be understood and dealt with.

A MODEL FOR THE ATTRIBUTES

These six attributes fit into a model of the manufacturing company as a business unit. A business is a process that converts inputs to outputs, making a profit as it does so. It is powered by resources, and subject to constraints such as laws of physics and of government. Figure 1.8.2 shows a generic process. The inputs on the left of the diagram are transformed to outputs on the right by the process, which is fed by resources from the bottom and subject to constraints from the top.

Figure 1.8.3 enables us to picture the essential dimensions of a manufacturing company, which are shown in Fig. 1.8.4, and to summarize the six attributes discussed previously [5].

To derive the diagram in Fig. 1.8.3 from the generic process model in Fig. 1.8.2, we identify the central significant items for each of the five factors in the generic process model. The sin-

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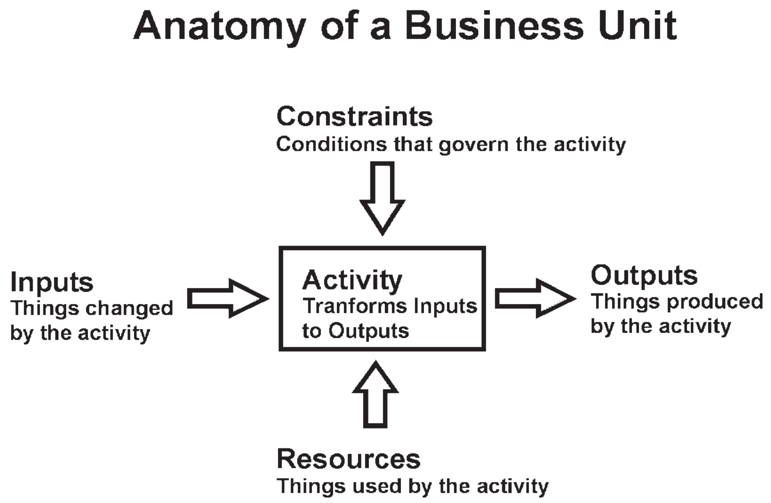
Anatomy of a Business Unit
Constraints
Conditions that govern the activity
Inputs
Things changed by the activity
Activity
Tranforms Inputs to Outputs
Outputs
Things produced by the activity
Resources
Things used by the activity

FIGURE 1.8.2 Anatomy of a business unit.

gle most significant constraint faced by a manufacturing business unit is the environment of constant, relentless, accelerating change. This then becomes the arrow at the top of Fig. 1.8.3. In order to deal with this, the internal structure of the company has to adapt. This requires that the culture and practices be responsive, together with responsiveness of the human resource and physical plant, and for this teaming a core competency is needed. A company that has successfully assimilated attributes 2, 3, 5, and 6 (see the list at the beginning of this section) will be adaptive and able to deal with the external change imposed upon it. These four attributes are incorporated inside the box in Fig. 1.8.3, which represents the company or business unit. The output of the modern manufacturer is more than just product. Using the product as a platform to supply a total solution, a fusion of product, service, information, and decommis-

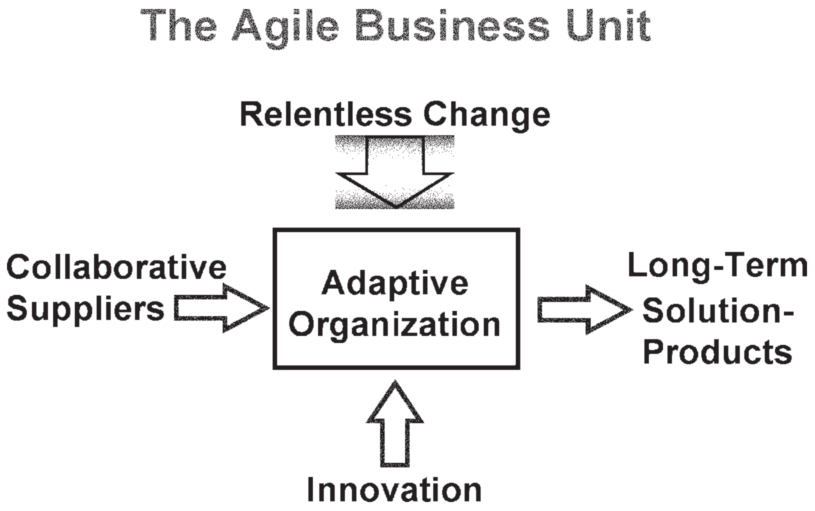
The Agile Business Unit
Relentless Change
Collaborative Suppliers
Adaptive Organization
Long-Term Solution-Products
Innovation

FIGURE 1.8.3 The agile business unit.

THE FUTURE DIRECTIONS OF INDUSTRIAL ENTERPRISES

sioning or recycling work, the manufacturer enters into a long-term, profitable relationship with the customer. If the customer is a commercial company (as is usually the case), the aim is to become part of the customer's business processes. If the customer is a consumer, the aim is to become part of his or her lifestyle processes. This is what Cadillac does by supplying the GPS navigation service, thus helping the driver navigate without having to stop and ask directions. Nike, the sports shoes distributor and manufacturer, does not sell shoes to protect one's feet, it sells status. The output of a manufacturer has gone beyond product; it is a long-term, total solution for which the product is a platform, as shown at the right in Fig. 1.8.3, and this is equivalent to attribute 1, customer responsiveness.

The manufacturer is an integral part of an extended enterprise. Pressures for reduced price and time, together with increased quality, are forcing manufacturing customers to require intense, ongoing interaction with suppliers. In the past, it was usual for the purchaser to supply the added-value engineering work needed to incorporate the bought component or subsystem into its product. The tendency now in the automobile and other industries is to require that the supplier provide that added-value work. The move to have suppliers work together to create entire subsystems, then to install them in the car at the assembly facility, is an example. This requirement can be a wrenching change for a supplier, but for those who manage to assimilate the attributes mentioned here, this change provides a competitive opportunity. This is represented by the arrow at the left of Fig. 1.8.3.

A summary of the changes in attributes of a company is shown in Fig. 1.8.4.

Enriching Customers with Total Solution-Products

FROM		TO
Product	⇒	Product + Service + Information
Product lines	⇒	Fragmented niche products
Point solutions	⇒	Total integrated package solutions
Supplying product	⇒	Integrating with customer's processes

Knowledge-Driven Enterprise

FROM		TO
Product is an aim	⇒	Product is a platform
Sale is one-time event	⇒	Sale is over lifetime
Information confidential	⇒	Information shared and confidential

Adaptive Organization

FROM		TO
Departments	⇒	Teams
Command & control	⇒	Empowerment
Managing	⇒	Leading
Hard tooling	⇒	Soft(ware) tooling
Passive equipment	⇒	Smart equipment

Cooperating to Enhance Competitiveness—Virtual Organization

FROM		TO
Supply a component	⇒	Supply a subsystem
One company at a time	⇒	Customer & suppliers work together
Price = cost + margin	⇒	Margin = price − cost
Arm's length	⇒	Common destiny with stakeholders

FIGURE 1.8.4 The four principal dimensions of the modern manufacturing enterprise.

ENABLERS OF THE MODERN MANUFACTURING ENTERPRISE

The attributes previously discussed describe the future enterprise, which will move from the characteristics on the left of the tables to the characteristics on the right. To develop those characteristics, a number of enabling, infrastructure systems need to be put into place. In the 1997 NGM report, these are termed imperatives because they are considered essential to movement in the desired directions. In the 1991 report, *21st Century Manufacturing Strategy* [3], these are referred to as enabling subsystems. This latter terminology will be used here.

It is essential to note an observation of companies that have implemented these subsystems—technology, people, issues, and business processes must be dealt with in a coordinated and integrated way. Almost all companies that have gone along the implementation path report missing the importance of this point. Attention to culture and the accompanying system integration issues is essential in all development efforts. To deal only with one or two while neglecting the remaining issues will yield quite unsatisfactory results. A corollary to this requirement is that there will be dilemmas in implementing the subsystems, situations in which one is "damned if you do and damned if you don't." Implementing the subsystems in a coordinated way means that companies, executives, professionals, and indeed all workers will find themselves in situations where they cannot see the way forward, yet there will be no retreat. This interesting challenge is unavoidable and will be discussed later.

Grouped according to the categories mentioned previously, the enabling subsystems are discussed in the following section. They are

1. People-related subsystems
   - Workforce flexibility
   - Knowledge supply chains
2. Business process–related subsystems
   - Rapid product and process realization (RPPR)
   - Innovation management
   - Change management
3. Technology-related subsystems
   - Manufacturing processes and equipment
   - Pervasive modeling and simulation
   - Adaptive, responsive information systems
   - Environmentally conscious processes and products
4. Integration-related subsystems
   - Extended enterprise collaboration
   - Enterprise integration

People-Related Subsystems

Workforce Flexibility. The set of practices, policies, processes, and culture that enables the employee to feel a sense of security and ownership enables a company to capitalize on the creativity, commitment, and discretionary effort of its employees, and at the same time maintain the flexibility to continually adjust the size and skills of the workforce. Toyota rewards managers not for their own ideas but for the ideas of the manager's subordinates, thus promoting leadership and teamwork and clarifying that the manager is a supporter of his or her group, not a "boss."

Implications for Enterprise Systems. The old mindset was that an enterprise was somehow "buying" an employee's capability. That concept could be viable in an industry with blue-collar workers who are expected to maintain a given output rate of muscle work. Today, and even more so in the future, production is based on much automation, and advantage is derived from innovation in everything the company does. Innovative capability cannot be bought; it walks out of the door every evening. The advantage of flexibility to the enterprise is obvious: making it responsive. The downside to the enterprise is that the people who constitute the flexible workforce are precisely those who find it easier to change to another company. The challenge to the enterprise is to maintain a culture and reward system that will maintain the loyalty of the flexible workforce to the company. These are illustrated in Fig. 1.8.5.

Implications for Leaders. This crucial issue presents interesting challenges for individuals because they must both help create the new, flexible environment and exist within it. Fellow team members must be coached, not managed, if all success factors are to be utilized. These issues call for systematic methodologies to exist at the enterprise level, but require custom-tailored attention at the individual level.

All of this places new burdens on the leader. Teaming and training decisions will have great impact on future capabilities of the workforce. Leaders must measure performance and adjust plans based on value, particularly in the long-term.

Key Success Factors

- *High number of skills per employee.* This is the defining measure of flexibility of the workforce. The higher this average number, the more responsive the enterprise will be.
- *Care in selecting staff.* As companies come to realize that the true assets are people, they are becoming more careful in selecting people. Many companies, such as Remmele Engineering in St. Paul, Minnesota (a company that deals in mechanical machining and fabrication), select people primarily on their values, knowing that it is easier to reskill people than to make them change values.
- *Speed to appropriately staff new situations.* Companies are learning not only to be careful whom they choose, but to institute a speedy process for doing the thorough staff selection needed.

The agile competitor understands that:

- People and information are the differentiators of companies in agile competition.
- People are successful agile competitors if they are:
  - Knowledgeable, skilled, informed about the company, and flexible in adapting to the organizational changes and new performance expectations demanded by changing customer opportunities
  - Innovative, capable of taking initiative, authorized to do so, and supported appropriately
  - Open to continuous learning, able to acquire new knowledge and skills just in time as requirements dictate, and technology-literate
  - Capable of performing well in cooperative relationships, on internal and intercompany teams that may be cross-functional and require multiskilled members
  - Willing to “think like an owner” and accept customer service responsibilities, acknowledge accountability, and accept ownership of problems and shared responsibility for the company’s success

FIGURE 1.8.5 The agile competitor. *(From* Agile Competitors and Virtual Organizations *[2]. Used with permission.)*

- *Continual push to improve workforce capabilities.* Continuous training and incentivization of the employees to improve both themselves and the work processes is a key success factor.
- *Use of temporary workers and outsourcing.* To deal with surges that come and go, whether over a period of weeks or a year, companies increasingly turn to temporary workers or to outsourcing. However, care must be taken to evaluate which capabilities are core and noncore. Moving core capabilities to temporary workers or suppliers can undermine the company's capability in key areas.

Knowledge Supply Chains. This is a new concept, important because, with the emergence of knowledge as a key competitive differentiator, a systematic method for rapidly and continuously injecting knowledge into an organization is needed. One can no longer rely on the sporadic and fragmented system of education, training, and consulting to bring that knowledge. Management, knowing that it needs to constantly update skills of the workforce, should proactively aim to create a system that facilitates a constant flow of knowledge throughout the manufacturing organization. Applying concepts of material supply-chain management to the relationships between industry, universities, schools, and associations may be one method of achieving this, as illustrated in Fig. 1.8.6. The large number of corporate universities is one reflection of this need.

As mentioned previously, companies like Motorola are finding innovative ways to create and maintain knowledge supply chains. In fact, Motorola's 1995 corporate manufacturing goals state, "Train employees for new careers outside of Motorola. Develop an alumni resource base that we will continue to support and which will continue to enrich the corporation and the customers we serve."

Implications for Enterprise Systems. The last decade has seen much activity in making the material supply chain more efficient. This has been achieved by proactive management of this activity. Most enterprises have until now relied on the generally available educational and research institutions, and on consultant services, to supply the knowledge needed. The enterprise will increasingly need to proactively develop knowledge supply chains, and this will often be in collaboration with the local community, government, and colleges.

Implications for Leaders. In looking beyond the immediate issues to plan the activities in which the enterprise should be engaged, the leader will be looking for efficient, cost-effective methods for generating reliable and up-to-date knowledge for the enterprise.

Key Success Factors

- Academic institutions, aided by industry, generate basic new knowledge.
- Academia takes new knowledge and creates educational methodologies for it.
- Industry creates new products and services based on new knowledge.
- Industry drives toward and supports continual education.

Business Process–Related Subsystems

Rapid Product and Process Realization (RPPR). This enabling subsystem results from integrating customer needs and wants with methodologies for systematic integrated product and process development (IPPD) and cross-functional integrated product teams (IPTs) in a computer-integrated environment (CIE). This is accomplished by interactively including all stakeholders, from concept development through product disposition, in the design, development, and manufacturing process. The difficulties of orchestrating this cannot be overemphasized. In the absence of a supportive culture and performance measurement and reward system, RPPR will not work.

The successful, cross-functional, platform teams used by Chrysler to design its successful LH and other series of cars (a technique now used by many companies) are an example of RPPR practice. This early, cross-functional integration has been shown to have significant, positive impact on life cycle cost, as shown in Fig. 1.8.7.

Implications for Enterprise Systems. Some years ago, when it became apparent that the old method of first designing then making a product as separate activities was too costly in time and

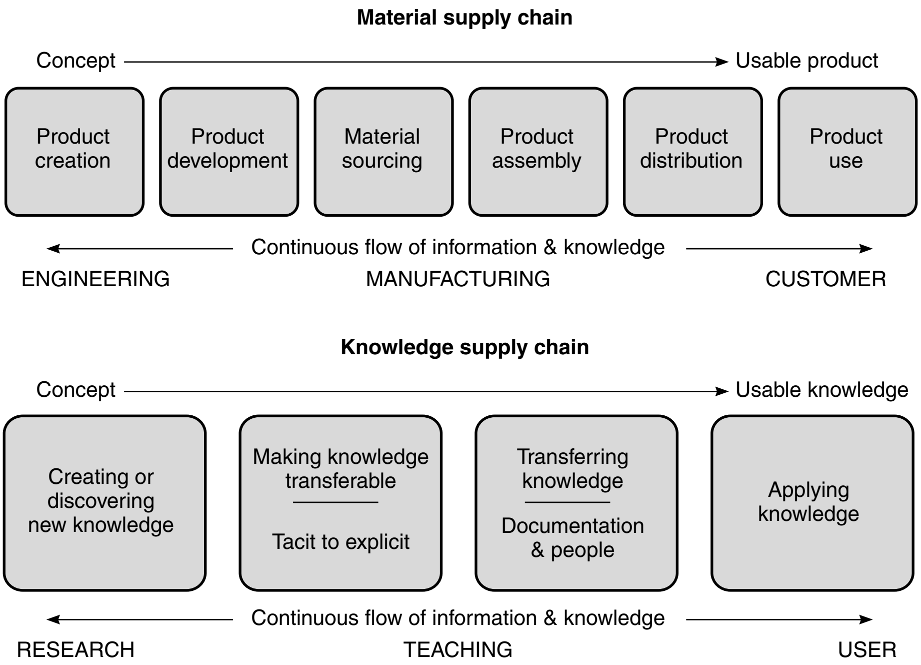
Material supply chain
Concept
Usable product
Product creation
Product development
Material sourcing
Product assembly
Product distribution
Product use
Continuous flow of information & knowledge
ENGINEERING
MANUFACTURING
CUSTOMER
Knowledge supply chain
Concept
Usable knowledge
Creating or discovering new knowledge
Making knowledge transferable
Tacit to explicit
Transferring knowledge
Documentation & people
Applying knowledge
Continuous flow of information & knowledge
RESEARCH
TEACHING
USER

FIGURE 1.8.6 Material and knowledge supply chains employ similar processes to achieve similar goals. *(From* Next-Generation Manufacturing Project *report [4]. Used with permission.)*

money, large efforts were made to map the activities and to set up formal systems to integrate those processes. That turned out to be impossibly difficult. The solution was then found not by trying to map the activities, but by putting people from the different activities together in a single team with joint responsibility for design of the product and the processes that produce it. Knowledgeable people who are correctly motivated will solve complex problems when formal methods fail.

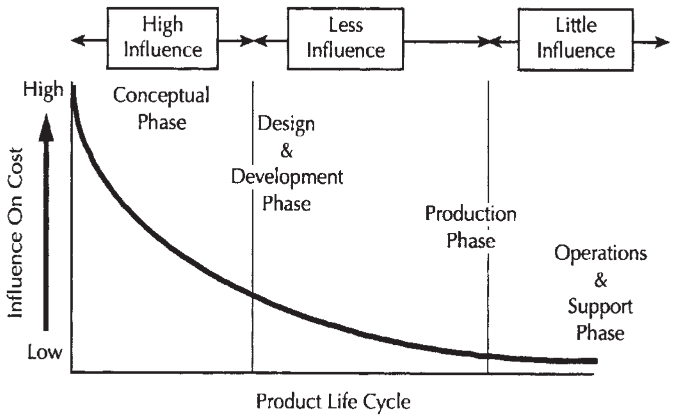

FIGURE 1.8.7 Early decisions affect life cycle the most. *(From* Next-Generation Manufacturing Project *report [4]. Used with permission.)*

Implications for Enterprise Systems. Some years ago, when it became apparent that the old method of first designing then making a product as separate activities was too costly in time and money, large efforts were made to map the activities and to set up formal systems to integrate those processes. That turned out to be impossibly difficult. The solution was then found not by trying to map the activities, but by putting people from the different activities together in a single team with joint responsibility for design of the product and the processes that produce it. Knowledgeable people who are correctly motivated will solve complex problems when formal methods fail.

Implications for Leaders. By emphasizing RPPR, leaders show that when quality and cost are taken as a given, time to market will determine the success or failure of an enterprise. This emphasis must be coached in a particular fashion so as to get the point across without sacrifice to other valuable contributions made to customers.

Key Success Factors

- *Customer satisfaction.* As response time for customers reduces, satisfaction increases as long as quality is not sacrificed.
- *Reward systems.* Opportunities for rewards systems exist on all levels such as company, team, and individual. These rewards must be based on new business practices required to generate RPPR.
- *Aggressive goals.* Goals should be set to clarify priorities in the workplace. Aggressive goals will help build up response capabilities based on given quality requirements.
- *Effective balance of focus on product and process.* While different companies will have different needs, each company must demonstrate the value of both product and process realization. RPPR relies upon the effectiveness of the system as a whole; therefore, the more integrated and coordinated product and process are with each other, the more likely it is that the company will create advantages based on speed.

Innovation Management. A systematic process for creating new profit from products and services comprises innovation management. Innovation is currently attempted by motivating individuals to creatively develop unconventional, out-of-the-box solutions. This implies that mavericks are needed, and that innovation requires breaking out of the existing system and thought patterns. However, studies of innovation are slowly leading to methodologies in which innovative solutions can be developed by systematic and deterministic methods. In other words, though the word innovation is often used for those developments that seem to be nonobvious fruit of unconventional thoughts and approaches, the border between systematic and creative development is gradually moving, so those solutions that seem innovative today will be achieved by systematic work tomorrow. The company and the individual that does not keep up with this development, or even try to lead it in their sector, will surely drop behind the international competition.

Innovation tends to flourish where fundamental constraints are lifted, and where an immediate sense of urgency is present. To successfully innovate, an environment must be developed where systematic encouragement of that innovation is nurtured and facilitated. Often confused with *invention,* which is characterized by an idea, innovation is characterized by successful use of an idea. This essential factor, commonly referred to as *exploitation,* is continually influenced by the aggressiveness of individuals, teams, and enterprises as they strive to compete.

As shown in Fig. 1.8.8, companies and enterprises can choose how they will operate within given markets. While it is true that profits can be realized through quick imitation, as product lifetimes shrink, future gains will increasingly go to the first mover.

Implications for Enterprise Systems. Innovative companies are powerful indeed, but innovative extended enterprises dominate markets. This can be difficult due to varying strategies for managing innovation. It is important that each company recognize that the same processes that help individuals and teams to innovate also apply to companies that are coop-

THE FUTURE DIRECTIONS OF INDUSTRIAL ENTERPRISES

erating to compete. Through this cooperation, speed creates advantage, as is evidenced by the previous discussion on RPPR.

Implications for Leaders. Innovative leaders need not be experts in innovation. However, they must be able to set the stage for innovation through creative management. This means taking and allowing risks, rewarding well-motivated innovation (whether leading to success or failure), and constantly clearing the paths to the future so that other innovators can plow forward.

Key Success Factors

- *Recognize the value of all (i.e., customers, suppliers, employees) possible contributors to innovative practices.* Through coordination, it is best to have more people innovating. Because innovation relies upon a clear flow of knowledge, channels must be created to ensure all voices can be heard.
- *Innovation management is a priority in strategic planning.* If executives concentrate on maintaining an innovative posture, it is far more likely that individual activities will contribute proactively to the future needs of the business.
- *People are motivated to innovate.* People will contribute in various ways, but if the company can find ways to motivate them, it can significantly improve the ability of the whole business.
- *Employees know how to learn from failure.* Leading innovators teach employees that failure is opportunity and that all steps are in the forward direction.
- *Innovative practices exist throughout the organization, not just in product and process design.* The company is made up of many processes; many of them can have sizable impact on business performance. Employees in the indirect process areas must understand how to contribute as significantly as do the employees in the direct areas.

Change Management. This system works to proactively manage change in a company. The rate of change of almost every factor affecting a company and its people is now so great, and accelerating, that occasional change projects can no longer be sufficient. Change is a process that needs management attention and nurturing. Beyond moving from one state to another state, change is a continuous process and requires proactivity both by companies and individuals.

Companies can craft change processes in a similar fashion as they do manufacturing processes. Through experience, it becomes evident which subprocesses cause failure or slowdown. Over time, methodologies develop that proactively create a solution from apparent catastrophe. Business process change usually involves more behavioral issues than does manufacturing process change, though it can be shown that common procedures apply to both.

Remmele Engineering provides both an environment and encouragement for change. It limits total employment at a single plant so change can be facilitated. It invests heavily in training so employees are ready to work on new and different things. It encourages contact with customers both to show customers how skilled its employees are and to let employees see firsthand what customer demands lie ahead.

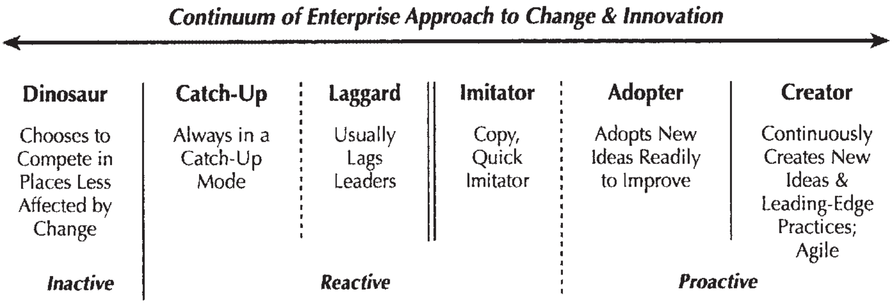
Continuum of Enterprise Approach to Change & Innovation
Dinosaur
Chooses to Compete in Places Less Affected by Change
Catch-Up
Always in a Catch-Up Mode
Laggard
Usually Lags Leaders
Imitator
Copy, Quick Imitator
Adopter
Adopts New Ideas Readily to Improve
Creator
Continuously Creates New Ideas & Leading-Edge Practices; Agile
Inactive
Reactive
Proactive

FIGURE 1.8.8 Continuum of enterprise approach to change and innovation. *(From* Next-Generation Manufacturing Project *report [4]. Used with permission.)*

Implications for Enterprise Systems. A constant challenge for change is the response time of the other companies within an enterprise. In modern business situations, leading companies have become much more integrated with their customers and suppliers rather than relying upon physical hand-offs alone. This means that strong links can help weak links by sharing successful practices. Long-term sustainability for companies within an extended enterprise will be as dependent on responsiveness as on technical capability. As markets inevitably shift, enterprises must be able to stay ahead in order to survive.

Implications for Leaders. Future leaders must understand that change is a process that can be mastered. People do not usually like change. Through effective management, coaches and contributors alike will learn to create opportunity from seemingly uncomfortable situations. The basic change process, shown in Fig. 1.8.9, needs to be custom-tailored and mastered.

Key Success Factors

- *Creation of a workable, custom-tailored change process.* This is the first indication that a company understands the value of managing change.
- *Effective leadership that understands the need for change.* Proactive change can only happen if managers facilitate and thoroughly support a comprehensive change process.
- *Infrastructures and network tools that facilitate change for individuals, teams, companies, and enterprises.* Change management cannot exist only in the intangible. Investment in hard resources must be made to take advantage of the leading edge.
- *Metrics and benchmark processes that support and enhance the change process.* By constantly testing and adjusting, the change process will always remain current and effective.

Technology-Related Subsystems

Manufacturing Processes and Equipment. These are required to support the rapid responsiveness and unpredictable change that the market imposes on the company. To do so, they must be flexible, reconfigurable, scalable, and cost-effective. Furthermore, the processes and

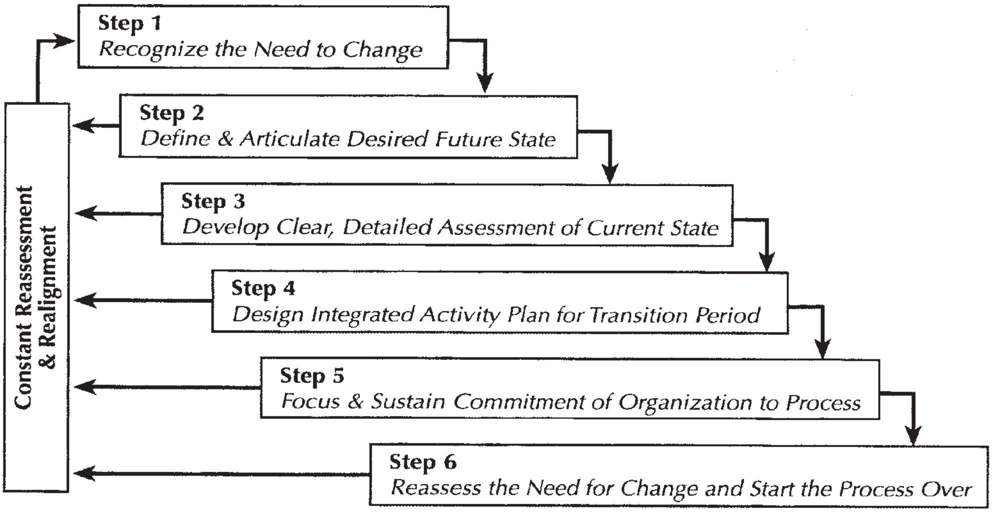
Step 1
Recognize the Need to Change
Step 2
Define & Articulate Desired Future State
Step 3
Develop Clear, Detailed Assessment of Current State
Step 4
Design Integrated Activity Plan for Transition Period
Step 5
Focus & Sustain Commitment of Organization to Process
Step 6
Reassess the Need for Change and Start the Process Over
Constant Reassessment & Realignment

FIGURE 1.8.9 The change model uses accepted precepts of effective change management, thereby providing a generic model for manufacturers to manage the transition to the next generation. *(From* Next-Generation Manufacturing Project *report [4]. Used with permission.)*

equipment cannot be considered independent of the knowledge and information systems that support their use. The rapid expansion of knowledge in general brings with it ever-growing knowledge of the science of manufacturing. This will allow more accurate production processes and reliable simulation and preproduction studies, thereby permitting a company to rapidly incorporate new processes and adapt to specific project or product requirements.

Lately, there has been a change in entrance fee to play and win in the marketplace. Previously able to compete through technology, companies invested heavily in manufacturing capabilities, often neglecting other indirect but supporting processes. Today, leading companies understand the crucial value of these other supporting business processes; however, they also see the need to excel in certain technologies. Neither technology nor business practice alone can create sustainable value for companies. In the production of leading quality integrated circuits, it is usual to find simultaneous development of both the product and the fabrication line that will make it. No one in that fast-moving and competitive industry would dream of first designing a chip, then thinking about how to make it.

Figure 1.8.10 shows the difference between the manufacturing processes and equipment of today and tomorrow.

Implications for Enterprise Systems. A successful enterprise should strive to maintain the makeup of its core competencies only while it is valuable to do so. Especially in manufacturing, companies must find a way to develop and deliver cutting-edge technology while enhancing customer value through interenterprise cooperation. Just as elements of the business (i.e., manufacturing, sales, R&D) must strive to integrate with other elements, companies should encourage technological alignment when confronted with new opportunities. Extended enterprises, not individual companies, compete for markets.

Implications for Leaders. In manufacturing companies of the past, technology was often taken for granted, subservient to the marketing or financing efforts. Success in the global marketplace will not allow such an attitude. As the rate of technology development and deployment in the world accelerates, there is the certainty that competitors, both old and new, will be developing new competitive technologies. The leader, therefore, should maintain an activity to track information on technological developments, and plan which technologies should be developed or acquired.

Key Success Factors

- *Ability to develop or reconfigure manufacturing to quickly respond to changing customer demands.* It is important to plan reconfigurabilty into processes so that customers will always be satisfied. If done successfully, this can easily become a key competitive advantage.
- *Enhanced company and extended enterprise understanding of technology and the ability to leverage it.* If technological capabilities are known and considered expertise on the enterprise level, manufacturing effectiveness will be maximized.

Today		**Next Generation**
Fixed Capacity	⇒	Variable Capacity
Recyclable Product	⇒	Recyclable Product, Plant, Property, & Equipment
Hard Tooling	⇒	Hard & Soft Tooling
Automatic Equipment	⇒	Autonomous Equipment
Rigid Plant & Equipment	⇒	Reconfigurable Plant & Equipment

FIGURE 1.8.10 Transition for manufacturing processes and equipment. *(From* Next-Generation Manufacturing Project *report [4]. Used with permission.)*

- *Abundance of motivated and skilled individuals who lead the company to markets.* As with many of the other enabling subsystems, the more people there are who possess and act on knowledge, the more likely the company will be to create and profit from new opportunities.
- *Ability to partner and team appropriately on both the company and extended enterprise level.* Cross-functional and cross-enterprise teams are better suited to coordinate critical competencies and design successful manufacturing processes that benefit all participants.
- *Establishment of standards that help supporting elements of the extended enterprise to communicate seamlessly.* Communication works best when all parties speak the same language. While there are many ways for companies in an enterprise to interact with each other, standards help prevent the possibility of serious, easily avoidable hardships.

Pervasive Modeling and Simulation. A growing need for these tools will follow from the deepening systematic, scientific understanding of production and business processes, especially multiorganizational processes. Virtual production, distributed across the globe and connected by information networks, will become more common. Production decisions will be made on the basis of modeling and simulation methods rather than on build-and-test methods. Modeling and simulation tools will move from being the domain of the technologist to a tool for all involved in product realization, for both production and business processes.

The Electric Boat Corporation has been involved in simulation of the human-machine interface in the development of the next generation submarine. In such tight quarters, the use of simulation tools for virtual prototyping becomes a powerful enabler toward optimizing the design. In similar fashion, the Caterpillar Corporation and other passenger vehicle compartment designers are using these techniques instead of building many versions of physical models.

Figure 1.8.11 shows the difference between the modeling and simulation of today and tomorrow.

Implications for Enterprise Systems. Modeling and simulation will help extended enterprises provide the means for member companies to clearly see effects of decision making on one another. This means that, ultimately, decisions may be made based on global interenterprise interoperability capability rather than individual manufacturing efficiencies. These modeling and simulation tools should bring more clarity to operations within the extended enterprise, allowing exploration of the implications of both small and large changes to the profit-making potential of a project.

Implications for Leaders. While it is not essential for leaders to completely understand the way modeling and simulation work, they must know what information to give it and what information it can provide. This requires regular learning opportunities and exposure through actual use. Tools such as this help to simplify complexity for management leaders.

Key Success Factors

- Establishment of standards
- Constant watch of developing computational and networking technologies for models that simulate technical and business processes

Adaptive, Responsive Information Systems. These can be reshaped dynamically by adding new elements, replacing others, and redirecting data flows by changing how modules are interconnected. The current generation of CAD and manufacturing systems, computer-aided planning, manufacturing resource planning, and similar systems are usually fragmented and not interoperable between companies, departments, or groups. The use of current standards such as STEP (Standard for Transfer and Exchange of Product Model Data) and the current technology of enterprise resource planning (ERP) systems have not solved this problem for two reasons. The first is that legacy data is usually not interoperable with these systems, and second, even when interoperability is established, new requirements and methods are constantly changed and updated.

Boeing, with the 777, has done more than most companies in achieving a "total digital product." Boeing's major, prime contractor partners all designed their key sections of the airplane using

Today		Tomorrow
Point Solutions	⇒	Totally Integrated Package Solutions
Customer Order (Off the Shelf)	⇒	Customer Specifies Product Requirements
Successive Hardware Prototypes	⇒	Iterative Software Prototypes Yield First Production Unit
Stand-Alone M&S	⇒	Integrated M&S on Design Critical Path to Support All Business Decisions
M&S Augments Design Process	⇒	M&S is Primary Mechanism to Refine Product/Process Design
Models Costly & Time-Consuming to Create, Difficult to Share	⇒	Libraries of Usable Models Easily Accessible
Models Not Available or Affordable	⇒	Availability of Models Driven by New Business Model
M&S Tools Proprietary or Closed	⇒	Interoperable, Networked M&S Tools
Discrete Event-Based Simulation of Manufacturing Processes	⇒	3-D M&S Incorporating Time, Dimensional Variation, & Physical Properties
Hard Tooling	⇒	Hard & Soft Tooling
Fixed Capacity Difficult to Adapt	⇒	M&S Tools Enable Management of Variable Capacity
On-the-Job Training	⇒	Hybrid & Virtual Prototyping Simulators Provide Embedded Manufacturing Education & Training
Controlled Intellectual Property	⇒	M&S Libraries & Tools Enable Collaboration & Sharing of Intellectual Property

FIGURE 1.8.11 Transition for modeling and simulation. *(From* Next-Generation Manufacturing Project *report [4]. Used with permission.)*

the CATIA CAD package. Other engineering, manufacturing, and simulation and modeling packages were integrated with CATIA so parts, subassemblies, and processes could be viewed electronically. The significant investment in capital, software, and training paid off since the electronically designed parts fit when assembled for the first time. Boeing treated the "electronic product/process database" as an asset that enabled the company to offset costly physical prototypes. However, this is not yet an adaptable and responsive information system as is needed. Adaptability and reconfigurability are predicted when common object request broker architecture (CORBA) and other new technologies mature. As shown in Fig. 1.8.12, future information systems must emphasize an integration of several enablers to have a chance of success.

Implications for Enterprise Systems. In approximately 80 percent of information systems projects, the development time is more than a year, and by the time the system is made, requirements have changed so it is obsolete without ever being used. For those systems in operation, it is a common complaint that the inflexibility of the system is an enormous inhibitor

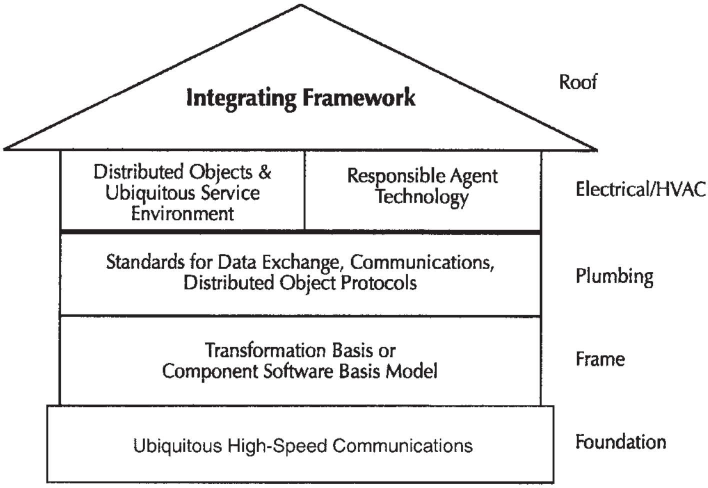
Integrating Framework
Roof
Distributed Objects & Ubiquitous Service Environment
Responsible Agent Technology
Electrical/HVAC
Standards for Data Exchange, Communications, Distributed Object Protocols
Plumbing
Transformation Basis or Component Software Basis Model
Frame
Ubiquitous High-Speed Communications
Foundation

FIGURE 1.8.12 Relationship among information system enablers. *(From* Next-Generation Manufacturing Project *report [4]. Used with permission.)*

of responsiveness and change in a company. Overcoming these factors by making information systems responsive and adaptive would be of great benefit.

Implications for Leaders. Information systems are too important to be left to a manager, invisible below a vice president or other executive. Just as war is too important to be left to generals, information systems are too important to be left to information systems experts. This is a field of rapidly changing technologies. Very few companies are able to have a team of experts in-house who keep up with the times, all the time. One impediment can be the creation of systems with too many options, most of which are marginally useful, and all of which are never available when needed. The leader needs to ensure that the specification process for the systems does not in itself force the systems to be inflexible and out-of-date, but rather that the information systems are constantly checked against the latest thinking and technologies in the field. In almost all cases, this will require bringing in outside experts.

Key Success Factors

- Standards must be emphasized if there is to be hope for pervasive, cost-effective use of new technology.
- Speed of information flow, usually tied to bandwidth, must grow significantly for companies to universally coordinate and control processes.
- Modularity and reuse of software components will have multiple benefits throughout industry.
- Research should be continually supported and monitored so that advances can rapidly be made usable in the competitive arena.

Environmentally Conscious Processes and Products. Government requirements for environmentally beneficial products and processes are not a driver but a result of public awareness and public pressure. The effect of human influence on the environment has now transformed the ethical values and social fabric of communities, from towns to nations. People now feel more environmentally responsible and seek appropriate action from business and governments that serve them. In the better-developed countries of the world, especially northern Europe, the requirement for environmentally coordinated product and process has been translated from the public desire to government decree, and is now a requirement for

THE FUTURE DIRECTIONS OF INDUSTRIAL ENTERPRISES

manufacturers and importers. This is a growing field of technology, and a competitive opportunity. Environmental considerations are becoming a multi-billion-dollar-a-year industry.

Implications for Enterprise Systems. Product and process are designed for so many factors that it is common to talk about "design for *x*." Environment is now an important member of that *x*. It must be considered in planning all product and all processes. Neglect of this factor may find a company limited in its access to markets and locations, globally. Note that when designing and making a product, each member of the value-adding chain must be involved in this effort, else all may suffer. If even one supplied component of a product does not comply with environmental regulations, the whole product may be unsellable. Similarly, if even one supplier uses a disallowed process, for instance with Freon, the whole product will be penalized.

Implications for Leaders. This is yet another item for which the leader must establish an organization capable of proactive management. This is not a job in which to park an unenterprising, loyal follower, but a job for a knowledgeable and proactive executive.

Key Success Factors

- *A culture of environmental responsibility.* Just as quality is not achieved when it is the responsibility of only the quality assurance department, so environmental responsibility is achieved when everyone in the organization feels a responsibility to this issue.
- *Supportive performance measurement and reward systems.* People act as they are judged, in this subject as in others. It is not enough for them to feel that the subject is important. They must know that the company values their efforts.
- *Easily available, updated information.* The information about environmental issues is rapidly and constantly updated and changed. This data should be easily available to anyone who wishes to find it.
- *Aligned standards.* A serious problem in the United States is that standards and requirements at the federal, state, and local levels are not aligned. As a result, a company that satisfies one legal requirement may find itself unavoidably in conflict with another legal requirement of another government agency. Companies should be aware of this pitfall, and government agencies should be aware of the problems they cause.

Integration-Related Subsystems

Extended Enterprise Collaboration. This integration-related subsystem is identified as an explicit subsystem because the context of today's manufacturer is the intensely interactive value chains to which it is connected. Manufacturers used to be stand-alone operational entities, passing product from one to another. The real-time exchange of information has created a situation where the work processes in one company affect other companies, immediately. Whereas previously a company could first organize itself, its structure, work methods, and culture, then look to customers and suppliers, the future company will first identify the value-adding chains to which it wants to be connected, then plan its systems and structure so that it can interact easily with the companies in those value-adding chains, and easily disconnect, reconnect, and reconfigure as it leaves or joins value-adding chains. A company that defines itself in terms of the products it makes ("we supply widgets for trucks") implicitly ties itself to the cyclic lows and highs of that product sector. The company, therefore, proactively manages its portfolio of value-adding chains to hedge so that when there is a low in one there will a high in another.

Figure 1.8.13 shows the transition in how companies interact with one another from yesterday to the next generation.

Implications for Enterprise Systems. An extended enterprise must make the same effort that its components do to continually improve. As more experience is gained and more study performed on extended enterprises, opportunities exist for learning that before could only be had through experience. Companies participate concurrently in more than one extended enterprise. Lessons learned from one need to be applied to another.

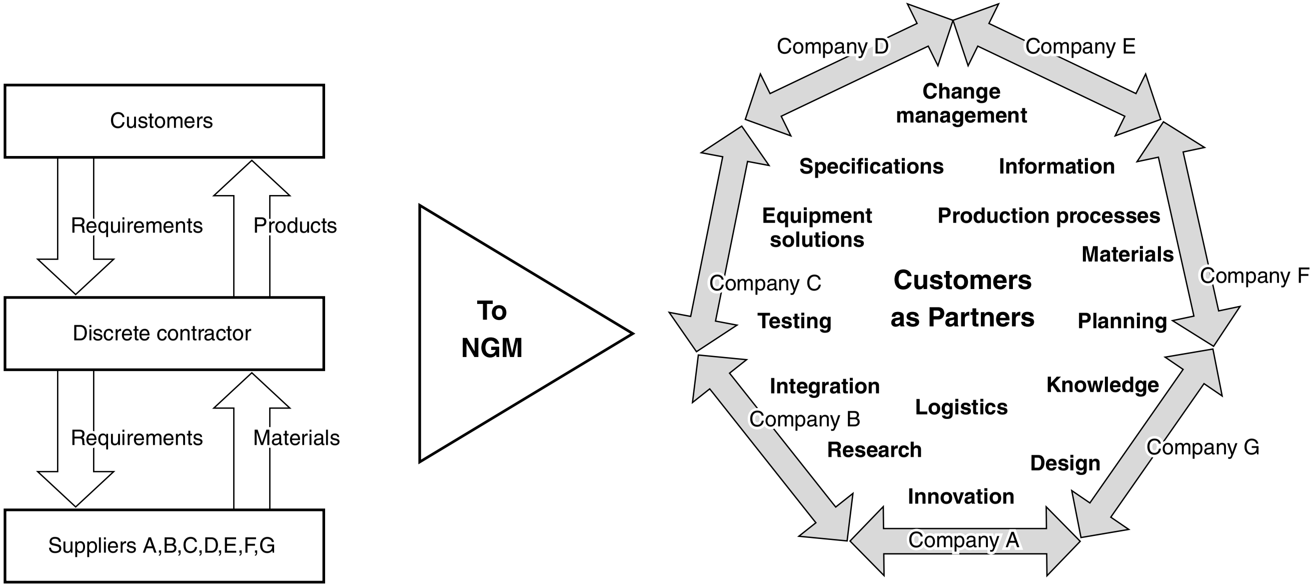
Customers
Requirements
Products
Discrete contractor
Requirements
Materials
Suppliers A,B,C,D,E,F,G
To NGM
Company D
Company E
Change management
Specifications
Information
Equipment solutions
Production processes
Materials
Company C
Customers as Partners
Company F
Testing
Planning
Integration
Logistics
Knowledge
Company B
Research
Design
Company G
Innovation
Company A

FIGURE 1.8.13 The new collaborative environment. *(From* Next-Generation Manufacturing Project *report [4]. Used with permission.)*

Implications for Leaders. Interaction with companies in the extended enterprise used to be a marginal item, secondary to all other strategic and operational questions. Today, it is a central item, a critical key to successful operation of a company. This means in practice that a senior person in the company has the responsibility for this activity.

Key Success Factors

- *Speed to develop trust.* In the time it takes to coordinate soft issues such as trust, another enterprise will capture market share. Companies must be willing to facilitate the mutual trust process in any way possible so that critical extended enterprise setup time can be minimized.
- *Existence of methodologies and standards for collaboration.* By creating methodologies, companies will be able to quickly join and leave enterprises in order to maximize mutual value.
- *Company commitment to the value of the extended enterprise.* Companies will participate in extended enterprises—intentionally or not. If corporate leadership does not design practices for the company to account for value of the extended enterprise, then many advantages will be lost, and it is likely that the company will be replaced in the extended enterprises in which it participates.
- *Ability to change the extended enterprise to meet new customer demands.* The whole of the extended enterprise is more important than any one participating company. All companies should know when contributions are effective and when it is time to seek alternative enterprise opportunities.
- *Ability of the extended enterprise to create new market opportunities.* Just as individual companies must innovate to remain competitive, companies in extended enterprises must work together to find profitable ways to continue to benefit from their organization.

Enterprise Integration. The system that allows people and systems within companies to collaborate is enterprise integration. It connects and combines people, processes, systems, and technologies to ensure that the right information is available at the right location, with the right resources, at the right time. It comprises all the activities necessary to ensure that the future company will be able to function as a coordinated whole. Some corporations have established vice presidents for enterprise integration. This is a difficult system to establish because it requires coordination of many technical systems, people, processes, and cultures. The difficulty should not inhibit starting along this road. As difficult as it is now to integrate people and systems, waiting while technical systems, structures, and fiefdoms expand and develop, makes integration even more difficult.

Figure 1.8.14 shows the fundamental levels of the company upon which enterprise integration must be based.

In 1988, the president of a U.S. $200 million per year manufacturer of electromechanical systems, each priced up to U.S. $500,000, was faced with a deluge of demand from his people for computer systems. Each request was for a different system, and each was amply justified. His decision was to let every group buy whatever system they wanted, within their budget, but subject to one condition. Each purchaser had to ensure that the computer system could exchange information with every other system in the plant. This forced the people to ensure interoperability. Within six months the policy paid off when an urgent order was executed (together with the essential testing and formal reporting of the product) within an extraordinary 10 days.

One of the more sophisticated infrastructures for global use of computers and communications systems is at British Petroleum. It has approached the technology as a means to draw together the talents of a decentralized organization. Emphasis is on the process of communication rather than on the transmission and accumulation of data. Modern capabilities (e.g., videoconferencing, multimedia, e-mail, and real-time application sharing) enable operating managers to talk more regularly and more informally—overcoming traditional barriers of geographical or business location. The result has been significantly enhanced communication and idea sharing, leading to increased efficiency and effectiveness in decision making, reduced costs, improved scheduling, and faster and more creative problem solving.

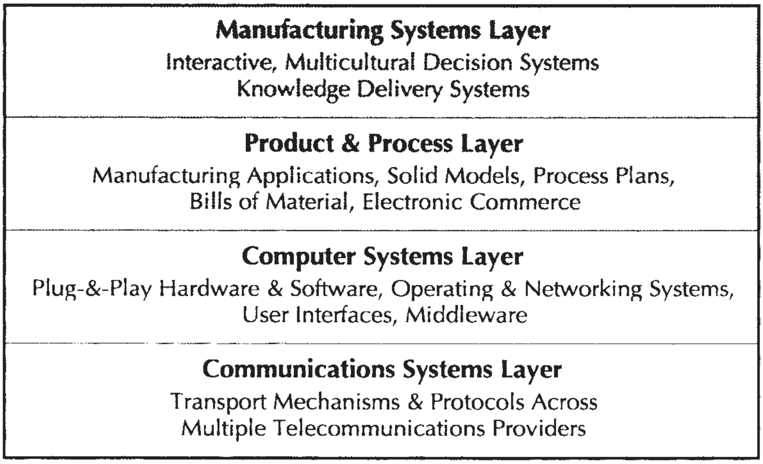
Manufacturing Systems Layer
Interactive, Multicultural Decision Systems
Knowledge Delivery Systems
Product & Process Layer
Manufacturing Applications, Solid Models, Process Plans,
Bills of Material, Electronic Commerce
Computer Systems Layer
Plug-&-Play Hardware & Software, Operating & Networking Systems,
User Interfaces, Middleware
Communications Systems Layer
Transport Mechanisms & Protocols Across
Multiple Telecommunications Providers

FIGURE 1.8.14 A future company's systems must operate at many levels. *(From* Next-Generation Manufacturing Project *report [4]. Used with permission.)*

Implications for Enterprise Systems. Successful enterprises establish processes that allow them to control activity and grow from that learning. In a manufacturing setting, this requires much more than scheduled meetings. Manufacturing process breakthroughs coupled with information technology's rapid advance has created unprecedented opportunities to link value-adding entities. Successful enterprise integration, allied with responsive technology and people systems in each operational unit, will enable strong enterprises to reconfigure faster than their competition.

Implications for Leaders. It is one thing to encourage integration of various subsystems in a company or enterprise; it is another to successfully pull it off. This task requires strong leadership throughout. It is not enough just to point in the right direction. Leaders must set clear goals and help others understand the paths to achieve them. Leaders will need to become more understanding of the interoperability of processes so that linkages can be secured by both technical and nontechnical means.

Key Success Factors

- *Established operational practices that permeate throughout.* These common practices allow the company to make cross-functional adjustments easily, because all processes operate to meet common core goals.
- *Organized information interchange that links all operations in the extended enterprise.* By establishing means of communication, enterprises invest in knowledge transfer and customer response.
- *Readiness to change practices and appropriately planned measures to ensure that operational needs are met.* Once integrated, all functions will be ready to meet new demands and know how each change should be tailored to support the other functions.
- *Use of tools and metrics that support and encourage integration-based operation.* Integration relies upon enhanced mutual effort. Thorough and constant assessments will reveal opportunities for improvement and show where current advantages can be better utilized.

METRICS

The future high-value-adding manufacturing company will be supplying a large number of individualized and total solutions, rather than a large number of identical products. As pointed out earlier, mass production has become a commodity process, which can be done anywhere in the world, and will gravitate to countries with cheap, but knowledgeable, labor.

As a result of the move to provide integrated, individualized solutions valued by the customer, metrics that monitor performance will change. Most people will work on implementation of the enabling subsystems, while actual manufacturing will be heavily automated. Because the ratio of direct labor to total cost will be so low, and because a relatively high fraction of cost will be due to collaborating suppliers and partners, today's metrics will either be unsuitably erroneous or insufficient. These common metrics are margin per unit of product, with its implied assumptions in allocating overhead and capacity utilization of systems. The need to deal with unpredictability while providing rapid solutions will make the capacity utilization metric, by itself, as useless for the individual production machine as it is for the telephone or office computer.

Financial measures alone will not be enough to manage the future manufacturing enterprise, because they do not separate out internal enterprise factors from general economic factors, and they do not give information as to how various operational factors affect a company's profitability. The following metrics are useful for management of a future manufacturing enterprise. Note that it is to be expected that a company will consider its people in two categories, core people and others. Those two categories will be used to manage manufacturing processes. Different industry sectors are likely to show different values of these metrics, and within a sector, leaders will have different values from the average company, but these are the kinds of metrics companies will likely use. The company will follow the trends in these numbers with time and will compare its numbers with customers, suppliers, partners, and competitors.

Average annual time reduction for all work processes (not only strictly manufacturing processes).

Example—17 percent per year reduction.

Average annual cost reduction for products and services in constant value dollars.

Example—3 percent per year reduction.

The average percent of the cost of products and services being spent with suppliers.

Example—89 percent to suppliers, 11 percent internal.

The skill scope of core people.

Example—the average number of skills of core people is 11.3.

The scope of core facilities.

Example—the quantity of products (stock keeping numbers) made in a facility is 840.

The turnover of core people per year.

Example—10 percent of core people left the company in the previous year.

The turnover of core productive facilities.

Example—the annual investment in core facilities is 11 percent of the total investment in production facilities.

Training effort.

Example—training budget is 7 percent of payroll expense.

Export effort.

Example—percent of revenue from non-U.S. customers is 45 percent.

Innovation.

Example—product and service offerings introduced during the last 12 months are 12 percent of the total.

Customization of product or delivery process.

Example—ratio of customized to standard orders is 56 percent.

MANAGEMENT OF DILEMMAS

The future industrial enterprise is being pulled into place by inexorable global drivers. These irresistible forces cannot be stopped. Companies and individuals must constantly reconfigure to take the best advantage of change. This is not easily undertaken. The new business environments, no longer characterized by clearly defined rules and methods of navigation, create an uncertain future.

The future will not be a smooth extrapolation from the past because the new demands are so different as to require new, counterintuitive approaches. Such a situation is not new in history, but is disconcerting to anyone who has come to maturity in the twentieth century, when the rules of organization were clear. For instance, when the methods of mass production were developed a hundred years ago, many people wrote that they would never work, because mass production requires that people arrive and leave work accurately at a fixed time, but human nature would never manage to do that reliably. Or, some decades ago, when the idea was put out that companies should achieve better quality at lower cost, this seemed to be impossible nonsense. Cheaper but better quality is indeed impossible if products are first made, then fixed. But, if made right the first time, better quality is, in fact, cheaper. Note that in both these examples, apparent paradox was resolved by going beyond the local details of the problem at hand and changing the total system and context within which the work was done.

A paradox is a situation where one is forced to simultaneously decide both something and its opposite; this is obviously impossible. A dilemma results from having to make a decision when faced with a paradox. There is a large body of theory dealing with the logic of dilemmas, and from this one thing is clear. A dilemma can be resolved only by changing the rules, or the context, within which it occurs.

Daniel Boorstin in his book, *The Discoverers,* writes that "science advances by grasping paradox" [1]. He gives many examples from every field of science where observations were made which ran counter to then-existing concepts, creating paradoxes. Only after a period of struggle and search was the paradox resolved by new ideas, which rearranged the systems within which the paradox occurred. Manufacturing science is now moving from an old perspective where progress was achieved by making improvements within existing concepts and systems, to a new challenge where progress is achieved by resolving paradox. In that sense, it can be said that understanding, analyzing, and designing manufacturing systems now approaches a level of maturity as a science.

The dilemmas facing manufacturing, for both executives and workers, are many. Each is a dilemma because of the conceptual environment within which it occurs. To deal with the dilemma one must go outside the issue at hand and change the concepts. There are many dilemmas in the modern business. No one knows for sure how to deal with them. The prominent leaders and companies will find their way to solutions; the rest will follow. Let us list some dilemmas with ideas as to how to manage them. These are written to raise the issues and should not be used as recommendations.

How Do Executives Empower People Yet Retain Management Liability and Responsibility?

On the one hand, a company in which managers need to approve every action is not only slow and unable to move at today's speed but is a company in which people do not use their initiative and knowledge, because having to get permission for every action stifles motivation. Teaming and empowerment are solutions deployed to speed up operations and make them more focused and innovative as the people become more motivated. Those are powerful advantages, yet when problems occur the legal liability falls squarely on the shoulders of executive management. So a company needs to empower people in order to become responsive and more efficient, but on the other hand cannot empower them because then someone may do something, even with the best of intentions, which causes the company to be held liable for serious damage. How do leaders deal with this? Maybe if all the empowered people were co-owners, they might see their responsibility in a way that minimizes adverse actions.

How Can We Give Needed Know-How to Suppliers, Partners, and Customers and Prevent Its Leakage to Competitors? As customers and suppliers in the extended enterprise bring their work processes together, they necessarily exchange data, some of which is confidential, relating to products, customers, and work processes. Many of the suppliers, customers, and partners of a project will work with one's competitors on other projects. Today's common sense would have us believe that this leads to the leaking of sensitive information to those competitors. How does one combat this? First, one must take care to analyze the information in one's company, with the aim of making as much as possible available, yet being careful to decide what information can be given to whom and under what circumstances. In the old world, the motto used to be, "All information is secret unless decided otherwise." Companies are starting to appoint vice presidents for knowledge and other similar functions whose jobs are to catalog, maintain, and plan the knowledge system. Also, companies are learning to be very careful to compartmentalize the confidential knowledge they have from other companies. If there are projects from two competitors, the people on those project teams would be kept separate. For example, the 264,000 ft^2 world headquarters and customer center for Delphi Automotive Systems (the world's largest and most diversified automotive supplier with annual revenue of nearly U.S. $28 billion) has extensive modern facilities to enhance interaction between customers and Delphi personnel, teaming to develop ideas and designs. The building was designed to enhance confidentiality, so that different customers (competitors) would not meet each other inadvertently. Since Delphi supplies components to more than 20 vehicle makers in the United States and foreign countries, new product plans can be discussed candidly and remain secret from other Delphi customers. An important reason for trust and compartmentalization to work is the longevity of relationships in an extended enterprise. When a relationship is short-term or one-time to sell product, there is little immediate reason beyond a sense of morality to keep a secret. But if the relationship is to be mutually profitable over a long time, there is hard-nosed business sense to keep a secret and not betray a trust. Otherwise, companies will find themselves expelled from profitable extended enterprises.

How Can There Be Employee Security and Loyalty Without Lifetime Employment? The need for companies to change structure and directions quickly, and for people to be flexible and trained in many disciplines, requires that it be easy for people to move from one company to another. But this contradicts the socioeconomic system in which a person's material welfare depends on long-term work with a permanent employer. The initiatives in the U.S. Congress to make benefits portable is a recognition of the dilemma caused when one's basic needs are tied to one employer. Here, culture and the practices that stem from it affect competitiveness. On the one hand, the existence of an economic safety net facilitates flexibility of workers; on the other hand, experience in many countries show that the safety net may be abused and encourage dependent behavior. This is a dilemma faced by many countries and companies today, and it is unclear how a redesigned safety net will be fashioned.

How Do Executives Make Strategic Plans That Necessitate Change Without Risking Their Jobs? This is a common dilemma faced by many people every day. The rate of change imposed from the outside on organizations today is so great, and increasing, that the internal structure of the organization must constantly change. But this is likely to make redundant the very people who need to decide on the internal changes. Levi Strauss dealt with this problem in a restructuring effort by undertaking not to fire anyone, then as they eliminated jobs, creating new job descriptions and requiring everyone in the company to apply for a post in the new system. Most people adjusted, a few could not and left, but opportunity was created for all who could cope with the challenge.

There are many more unavoidable dilemmas. Some are listed below, and the reader can doubtless think of others.

How can we simultaneously satisfy all stakeholder needs?

How can a company control core competencies without owning them?

How is it possible to recover rising plant and equipment costs with shorter product and process lifetimes?

How can entrepreneurs and companies foster new markets without creating competitors?

How can a company develop global markets and keep domestic jobs?

How can employees have good jobs with individual security while employed in flexible workplaces?

How can an organization have a few selected customers and suppliers yet prevent them from taking control?

How can we implement standards that are accepted, up to date, on time, and do not inhibit using the latest technology or work methods?

How is it possible to keep stability in quality and safety of manufacturing processes when processes change rapidly?

CONCLUDING REMARKS

Analysis of the drivers of modern competitiveness leads to the identification of necessary enterprise attributes, which leads to a recognition of barriers to overcome in moving the enterprise forward, which leads to identification of necessary enabling subsystems. These were all identified in this chapter. Attainment of the necessary attributes and implementation of the enabling subsystems require managing complexity, and in doing so, living with ambiguity and working through dilemmas.

What appears complex today appears simple tomorrow as that complexity is mastered. Historically, progress in managing companies and manufacturing systems is a story of managing the complexity of companies of increasing size and interconnectivity within themselves and with other companies.

The future industrial enterprise will be an adaptive organization able to simultaneously deal with more conflicting issues than are currently thought possible. It will have mastered quality, speed, and cost, and will manage complex interdependencies with suppliers, customers, partners, employees, governments, communities, and interest groups by maintaining intense interaction with all. It will simplify and modularize business and technical processes and product components as a means for mastering complexity. Even as the new structures and automation will reduce the number of jobs in traditional hands-on manufacturing work, new jobs will develop requiring the skills to implement the enabling subsystems, which will underpin every manufacturer's competitive capability. Manufacturing is developing as has agriculture—though the number of farmers actually working the fields has decreased significantly, the number of people working around farming and the production, distribution, and preparation of food has increased.

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BIOGRAPHIES

Kenneth Preiss is an honorary member of the American Society for Mechanical Engineers. Dr. Preiss holds the Sir Leon Bagrit chair jointly in the Engineering and Business Schools at Ben Gurion University in Beer Sheva, Israel. He has held leadership roles in defense and industrial projects in Israel and in the United States and has worked in areas ranging from artificial intelligence to mechanical and civil engineering, from desalination and solar energy to oceanography.

Dr. Preiss was coleader and coeditor of the seminal 1991 report to the U.S. Congress—*21st Century Manufacturing Enterprise Strategy: An Industry-Led View,* and of the 1997 industry report to the U.S. National Science Foundation—*Next-Generation Manufacturing.* His published works include over 200 original research papers and reports. He coauthored both *Agile Competitors and Virtual Organizations: Strategies for Enriching the Customer* and *Cooperate to Compete: Building Agile Business Relationships* with Steven Goldman and Roger Nagel.

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Mr. Patterson was a contributor to the development of the *21st Century Manufacturing Enterprise Strategy* commissioned by the office of the Secretary of Defense. He was coleader of the *Next-Generation Manufacturing* (NGM) project commissioned by DARPA and the National Science Foundation. He has spoken, including keynote presentations, at conferences in the United States, Asia, and Europe on topics such as emerging competitive concepts, the shape of industry in the future, and how to position your organization to be a next-generation enterprise.

Mr. Patterson also sits on the boards of the National Coalition for Advanced Manufacturing and the Automation and Robotics Research Institute.

Marc Field is a leader in strategic supply-chain issues and in agile organizations. He has experience working with leading e-commerce, high-tech, and CPG companies, helping them to develop, market, or select e-business solutions. Prior to joining Benchmarking Partners, Field worked as a project manager at the Agility Forum where he helped manage the *Next-Generation Manufacturing* project and helped manufacturing and governmental organizations develop supply-chain partnerships and other strategic initiatives.

CHAPTER 1.9

THE ROLES OF INDUSTRIAL AND SYSTEMS ENGINEERING IN LARGE-SCALE ORGANIZATIONAL TRANSFORMATIONS

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Increasingly, improvement efforts in organizations are larger, more comprehensive, and more complex. The relentless pursuit of increasingly higher levels of performance is forcing leaders to adopt systems thinking as a way of doing business. This situation has revitalized interest in strategic planning, not so much because it is strategic, but because, when done well, it incorporates alignment and attunement and is effectively deployed throughout the organization—it creates improved results. Improvement efforts are now often viewed as large-scale and organizationwide, enterprisewide. The enterprise often is viewed as extending upstream to partners (suppliers/vendors) and downstream to customers. The systems background of most industrial and systems engineers (ISEs) makes them natural potential contributors to such large-scale, systemwide improvement efforts. This chapter gives the reader a glimpse at what large-scale improvement efforts can be and where and when ISEs can fit into these efforts. It is not a given that ISEs will play a key role in large-scale improvement efforts. We believe that these opportunities must be earned, must be seized. We offer this paper as an initial blueprint expanding the domain of our profession.

BACKGROUND

The organizational environment of the 1970s and 1980s was characterized by improvement fads—programs of the year, so to speak. In the face of increasing change, risk, and uncertainty sparked by new technology, as well as an increasingly global economy, efforts to regain competitiveness were piecemeal at best. Organizations sought simplistic solutions to complex issues. The 1990s saw a growing recognition of the lack of comprehensiveness and integration of improvement efforts. From our vantage point, we began to see a change both in the literature and in corporate initiatives intended to bring this disparate landscape together. The organizational development work of the 1960s was revitalized and made contemporary by Deming and Senge and others. Total quality management (TQM) was perhaps the early version of what has been evolving. Today, improvement is more complex, more dynamic, and more demanding; it requires a balance of solution delivery and change management knowledge and skill. The trend has been away from independent improvement projects and project management technology toward program management with integrated improvement projects. It's like improving one's golf or tennis game—you can't neglect any one aspect, you have to be working on the whole game all the time. The challenge facing organizations is to effectively accomplish what others have called large-scale, systemwide transformations that encompass a wide variety of programs and projects.

Our profession is at a critical juncture. ISEs can continue to simply be project managers or we can also be players in the strategy and policy development for overall large-scale, systemwide transformation. The direction we take should be to strive for an "and" and not an "or" situation, however. Making it so has to be on the initiative of ISE leadership working within individual organizations. Left to its own course, we believe that the default position will be to relegate the ISE function to specific projects within a larger program for improvement (e.g., setting standards, plant layout, optimization, workplace redesign, forecasting, simulation). We believe that ISEs can and should play a larger role in corporate and organizational transformation. Our systems background makes contemporary ISEs a natural part of the team that strategizes such transformations. This chapter provides examples in which this metamorphosis has happened. It gives the reader a glimpse of what is possible.

We begin by describing a method for large-scale transformation and as we do so, we also describe, and you can infer, the roles that ISEs can play in such transformations. Are we suggesting that projects such as establishing standards, forecasting customer demand, improving facility layouts, or optimizing inventories are no longer the bread and butter of ISEs? *No.* Are we suggesting that selected ISEs can and should also play key roles in the bigger picture? *Yes.* Can ISEs help senior leaders understand which projects to focus on and how they all fit together to optimize (achieve the full potential of) the total system? *Absolutely.* We provide examples where this has happened. We are calling for more of it to happen and as it does, we are confident that the image and identity of our profession will be enhanced.

WHAT KEEPS EXECUTIVES AWAKE AT NIGHT?

What are the burning issues? What keeps top leaders awake at night? Ask a group of executives this question and you'll get answers like this: "These mergers and acquisitions create lots of turmoil; what happens when you can't merge and consolidate anymore?" "The gains from mergers, the growth rates are so much higher than from just working improvements within an organization. How do we keep up satisfactory rates of improvement once the merger mania is over or when it isn't an option anymore?" "How do I do all the 'B work' (building the business, improving things) in the face of a tremendous amount of 'A work' (administering the business, doing the job) and 'C work' (catering to crises, fighting fires)?" (See Fig. 1.9.1.) "How do we drive out the 'D work' (doing the dumb, non-value-adding stuff)? How do I find balance in my life given the increasing pressures to excel at 'A' and 'B' and 'C'?" "Where does this all end? There seems to be no end to the changes." "Why can't life be simple anymore?" "Is the business of improvement really this complex?" "How do I get and retain good people? How do I develop them and not lose them?" "How do I downsize, or right-size, and still have integrity relative to my culture, my values?" "Why can't I just run my business, live from day to day, week to week, like I used to?" "Why do I have to have a plan?" "Why do I have to do all this teamwork stuff? The command and control approach works well and faster and I know the business better than most of the others anyway." "I'd like to retire but don't know what I'd do if I did and besides, they couldn't run the business without me." "How do I establish 'B work' and sustain a culture where people see 'B work' as part of their jobs?"

These executives want growth and they want improvement. They want to be successful. Many also want to keep doing what they've always done. Significantly different results require significantly different methods. Many top leaders resist change. They will tell you they struggle with resistance to change in the organization, but what they really mean to say is that they struggle with resistance to change in themselves. We all fight this battle, of course. Steven Covey tells us that real change is an inside-out proposition. We believe that many of the situations that top leaders of organizations large and small are facing are caused by faulty methods for improvement. Their "B" processes are flawed or non-existent. They think they are doing "B work" but they really aren't. So, let's look at an example of how to do "B" at the organizational level and let's think about the role of ISEs in establishing such systems in organizations of the future.

THE METHOD—AN EXAMPLE OF LARGE-SCALE TRANSFORMATION

Transformation starts with the team at the top. As Katzenbach [1] points out, focusing on the word "team" may be misleading. Top leadership and management groups are often not

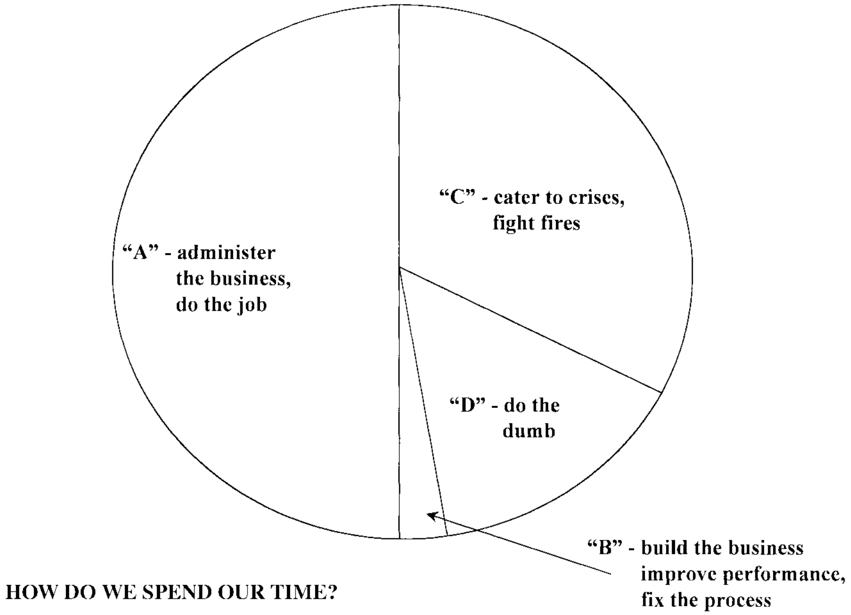

FIGURE 1.9.1 ABCD model.

basketball-type teams (i.e., ones in which peak performance requires a high degree of teamwork); they are more like track teams (in which peak performance is the sum of individual performances). Some leaders are on track-type teams that get along and some are on ones that don't. In our experience, leaders who engage in competition within and among units don't get along and therefore cause underperformance. Katzenbach goes on to contend that what is required is greater flexibility regarding the type of teamwork that is invoked in specific situations. Be a great basketball team when the situation requires it, but don't lose the ability to be a great track team at other times. He suggests that the individual excellence is generally present in great top leadership and management groups. What is needed is more work to build the capability for great basketball-type teamwork when it is needed. Transformation starts inside each member of the top team, beginning with the CEO. At this point, we aren't aiming to change leadership style, we are aiming to create more awareness of leaders' paradigms, assumptions, methods, tendencies, strategies, and actions. This is a process in and of itself.

We have been experimenting with what we call "development sessions" for top leaders. A development session is an integration of strategic planning activity, work to adjust mindset or "condition" of the mind, and team building. The outcome is a group of enlightened, aligned, and accountable individuals with a common language, trust, commitment, and the potential to be a high-performing team. They simultaneously work on personal mastery, team building, and strategic planning. They start with an investigation into what is possible, what the full potential of the organization is. We utilize the findings of Collins and Porras [2] in their book entitled *Built to Last* as a way of sparking dialogue. Here is the essence of how we use that study:

> Collins and Porras studied companies that were in business for over 70 years. One set of companies performed "excellently" in that $1 invested in 1920 was worth $6400 in 1990. They matched these with a set of comparison organizations, and compared and contrasted how the matched companies fared. These "good" companies parlayed $1 into $900. The authors formed a control group by randomly sampling other 70-year organizations from the Fortune 500, and found that $1 invested in them became $450. The central question is, "What is the difference among these sets of organizations?" The $6400 Companies were excellent in doing "B work" as well as "A," and handled "C work" well. They found out that the $900 Companies were good at the "A" and "C work" of running the business, but were not particularly effective at "B." The $450 firms that were pretty good at "A work" and struggled with "B" and "C work." (Note that another group—companies good at "doing the dumb"—didn't last the requisite 70 years to be in the study.)

Once they understand the concept of built to last and full potential, we ask the members of the top team what results they want to produce. Most often they will say they want to be a $6400 organization. Then we ask what results they actually have created. Many will say they have fallen short of $6400; perhaps they are closer to $1000 or $2000, but they insist that they are "trying hard" to be $6400 organizations.

Conditioning of the Mind

At this point the conditions are usually such that the development session can either continue to work on strategic planning or we can work on mindset. When working on mindset, we focus on the use of words like "try" and "hope," and the condition of the mind that they reflect. We point out how those words can affect results—because they provide ready-made excuses for failure. (In the event of failure, you can always point out that you tried, which is actually all you promised in the first place.) In this case, the leaders' language is related to their intention. We suggest that if they really intended to be a $6400 organization, they would be. We also contend that if their stated intention doesn't match the actual performance, performance is the true index of intention. In other words, even if they say that they are a $3000 organization "trying" to be a $6400 organization, in fact, all they really intend is to be a $3000 organization. We use the intention/mechanism model (see Fig. 1.9.2) to make our point.

Here's how the model works: Define two views of the world. We'll call one the $6400 view and the other the $1000 view. The $6400 view is rare today; most organizations don't exhibit the attitudes or behaviors that support the $6400 performance. The $1000 performance is common today and is typical of organizations "trying" to continuously improve. According to the intention/mechanism model, one can know intention by the results produced (i.e., results are totally a function of intention). Once one agrees to adopt this view of the world, interesting conversations develop. Suppose an organization produces a performance gap (a difference between what it creates and what it intends to create). Among persons with the $6400 view, conversations focus on understanding root causes of the gap and learning how to reduce error in the future. For those with a $1000 view, conversations focus around fixing the blame and explaining what happened and how it wasn't "my" fault. In the $6400 view, people are clearly connected to results, to error, and to reducing error. In the $1000 view, people are not connected to results, to error, and to reducing error. In the $1000 view, people search for, invent, and create stories that fix the blame for error on something other than intention—they blame mechanism. In the $6400 view, you search, invent, and create solutions for achieving the results you intend and don't accept less. There are no uncontrollables in the $6400 view. Everything is in the organization's sphere of control and influence. The $6400 organization requires a critical mass of people who live, eat, and breathe the $6400 view. Clearly, this perspective will lead to much discussion and often much debate.

Achieving $6400 performance requires what Argyris [3] calls double-loop learning. The governing values held by people are (1) utilize valid information; (2) promote free and informed choice; and (3) assume personal responsibility to monitor one's own effectiveness. The action strategies associated with double-loop learning are (1) design situations or environments where participants can be original and can experience high personal causation (psychological success, confirmation, essentiality); (2) protection of self is a joint enterprise and oriented toward growth (speak in directly observable categories, seek to reduce blindness about one's own inconsistency and incongruity); and (3) protection of others is promoted bilaterally. The outcomes from the application of double-loop learning are (1) learning is facil-

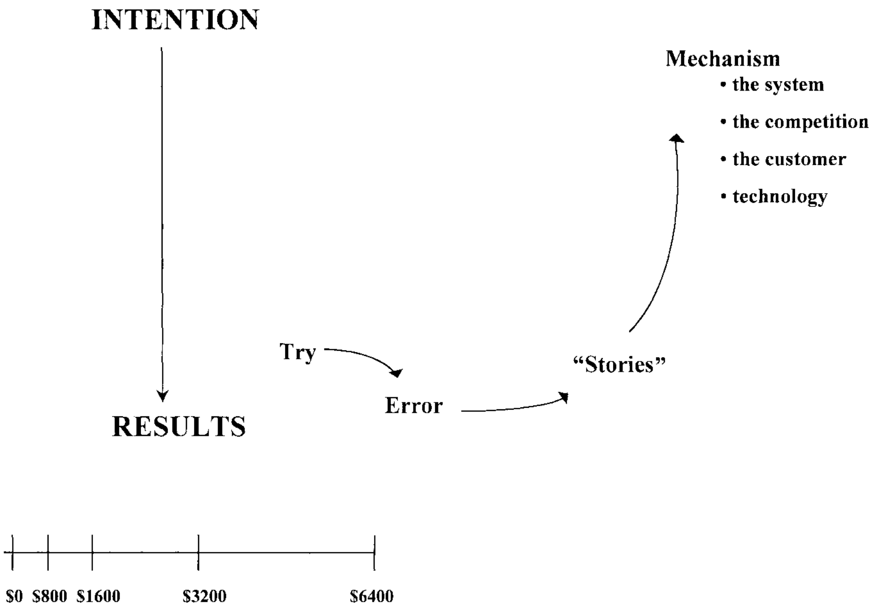

FIGURE 1.9.2 Intention/mechanism/result model.

itated; (2) persistent reduction of defensive organizational routines is facilitated; and (3) double-loop learning is generated.

The $1000 performance, which we see most often, utilizes a different type of learning and behavior. The governing values in this model, according to Argyris, are (1) be in unilateral control of situations; (2) strive to win and not to lose; (3) suppress negative feelings in self and others; and (4) be as rational as possible. The action strategies are (1) advocate your position; (2) evaluate (judge) the thoughts and actions of others (and even your own thoughts and actions); and (3) attribute causes for whatever you are trying to understand. The learning outcomes are (1) limited or inhibited learning—we don't seek to understand very much; (2) consequences that encourage misunderstanding; (3) self-fueling error processes—error persists and can even increase; and (4) single-loop learning—we may understand causes (probably symptoms) and we are often fixing the problem rather than the process.

The $6400 organization detects and corrects error by first examining underlying values, assumptions, and paradigms. The $1000 organization says, "Oh, something is wrong. I'll explain it away to things outside my control."

One way to characterize the condition of the mind we promote in the development session, is what we call the "at-cause" mindset. (An *at-cause* person accepts the organization's vision, will do whatever it takes to have the organization succeed, and takes personal responsibility for making it happen.) Many, perhaps most, successful leaders have this mindset but, unfortunately, few know what it takes to re-create it in those around them. The $6400 organizations are filled with associates who exhibit this mindset and its accompanying behaviors. To be successful in the new role, an ISE will have to adopt this mindset and exhibit it as a natural characteristic. Take some time to reflect on the attitudinal difference between people who achieve results and those who are always "trying" and "hoping" but never quite able to make things happen.

Strategic Planning

Once we have spent some time on mindset, we return to the strategic planning and creation piece. Note that often this is somewhat recursive in nature—we work on mindset, then on planning, then back to mindset, and so on. No matter what, we always focus on what the leaders of the organization want to create. We work to help them get focused and clear on their point of arrival. To support this module, we suggest that they pick a time in the future—a period of time beyond the normal operating horizon, but not so far out as to create a disconnect. Typically, this time frame is from three to five years. We ask the top team to articulate what results they want to create on or before that point in time. What's their vision? What are the possibilities? What business results do they want to have created by the end of this period? What businesses are they now in? How are they performing? What technologies (broadly defined) do they employ? What do employees, stockholders, customers, and suppliers experience about them? What was their destination and what does it feel like when they get there?

Another simple model (see Fig. 1.9.3) will assist us in introducing some subtlety into our approach.

If you identify the results you want to create from the perspective of your current reality, you define the future with your mind in the present and identify one set of desired results. If you take your mind out to the future and experience the realization of your possibilities, you will identify a different set of desired results. You will discover things you want that you couldn't identify while anchored in the present. This is what we do with the top team. We get them to begin thinking in a "future perfect" sense. This exercise also works when you think through strategies and actions. If you go out to the future, imagine having created a certain desired result; then look back and ask what you did to achieve that result. This is different from standing in the present and thinking through strategies and actions from the present forward.

We work on point of arrival until there is sufficient clarity and conviction to move on to the next step. A simple way of thinking about point of arrival is that it is an operational definition

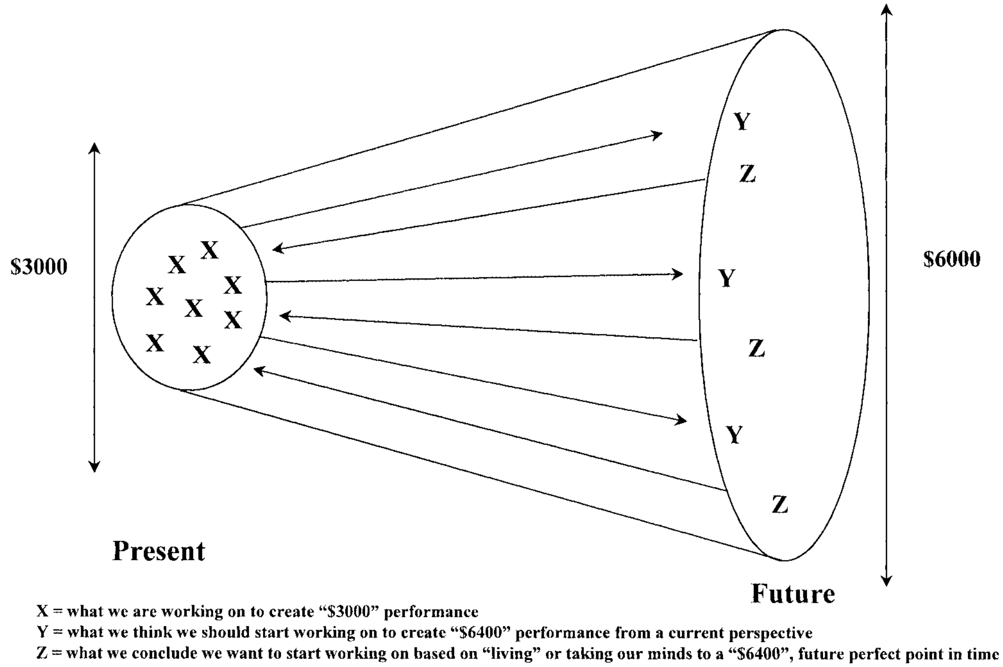
$3000
X
X
X
X
X
X
X
X
X
$6000
Y
Z
Y
Z
Y
Z
Present
Future
X = what we are working on to create "$3000" performance
Y = what we think we should start working on to create "$6400" performance from a current perspective
Z = what we conclude we want to start working on based on "living" or taking our minds to a "$6400", future perfect point in time

FIGURE 1.9.3 Megaphone model.

of what success looks like and feels like at some point in the future. During this process the top team is defining an equation specifying what success equals. It takes many repetitions to get people connected to the end, to get them to internalize what they want as a team. We strive for alignment and attunement. Alignment occurs when all are basically headed in the same direction, toward the same end point. Attunement has to do with the tightness of fit, the cohesion of the team—the culture of the team, if you will. Our experience strongly suggests that most top teams lack alignment and attunement. Most are not clear on their point of arrival. When you're not clear about what you want you can muddle your way through things. Muddling through things doesn't create $6400 organizations.

Building and Using the Planning Wall

Once the point of arrival is clear and shared (this often takes two to three days of focused work), we can look at the work breakdown structure for the organization. We are asking you to identify the work in front of you as you create your point of arrival. In the process, we create a planning wall. The left side of the wall is where we portray the past and present—the significant events that brought the organization to where it is today. The right side of the wall shows the future, the point of arrival that the top team intends to create. The middle part of the planning wall will contain the work breakdown structure—a breakdown of the work you have to do in order to succeed. A simple way of thinking about this is that you are answering the question, "What will create success?" or "What do we have to do to succeed?" As we have already indicated, it is useful to have the top team think in future perfect terms, to mentally go to the future and look back. In this exercise, they would be experiencing success and thinking through what they did to cause that success.

The building of the middle part of the planning wall prompts a "start, stop, continue" discussion. (Given the work ahead, What should you start doing? Stop doing? Continue doing?) This exercise can be aided through the development of a model of success. The model of success is a causal model. It is a picture of beliefs in cause-and-effect relationships for the organization. In "The Employee-Customer-Profit Chain at Sears," Rucci, Kirn, and Quinn [4] provide an excellent example of the model for success (see Fig. 1.9.4).

To the far right side of the model is the stockholder value exchange: Sears wants to be a compelling place to invest. There are key performance indicators (KPIs) that tell them how they are doing relative to particular indices (e.g., return on assets, operating margin, revenue growth). In order to be a compelling place to invest, they believe they need to be a compelling place to shop. Customer impression is important and customer impression is shaped by service quality (in-store interactions) and merchandise availability and value (quality/cost relationship). Employee behaviors are shaped by employee attitudes and these behaviors strongly affect customer impressions and behaviors. Thoughts are expressed in words that then show up in deeds. Sears measures employee attitude about the job and the company. They have found through fairly rigorous data collection and analysis that a 5-unit increase in employee attitude drives a 1.3-unit increase in customer impression which in turn drives a .5 percent increase in revenue growth. The interesting thing about the Sears case study is that it focuses on the value exchanges between the organization and the investor, the organization and the employee, and the organization and the customer. All three exchanges are critical to the achievement of full potential.

Models of success are systemic, pictorial representations of one's beliefs in cause-and-effect relationships (mental models). We are concerned, at the outset, less with the correctness of the model(s) than with the learning that comes from articulating the relationships, and with the learning that then comes from collecting data on the behavior of the variables and correlations among them. The point is that until you define success and what success is a function of, planning really can't be effective. One can do planning in the absence of the model for success, and many do. However, one inevitably ends up with a hodge-podge of strategies, actions, and measures that may or may not, in fact, lead you to realize your full potential. The value in creating a model for success is that it forces dialogue about assumptions, hypotheses, mental models, and beliefs in cause-and-effect relationships. Measurement over time allows you to test all this.

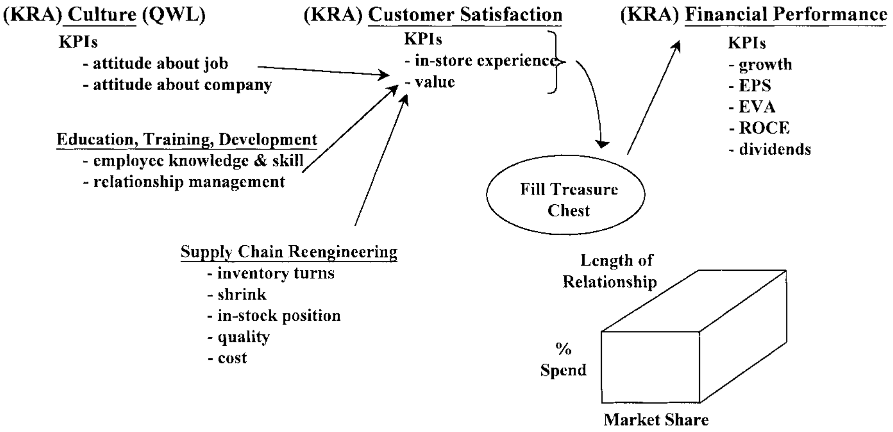
(KRA) Culture (QWL)
KPIs
- attitude about job
- attitude about company
Education, Training, Development
- employee knowledge & skill
- relationship management
Supply Chain Reengineering
- inventory turns
- shrink
- in-stock position
- quality
- cost
(KRA) Customer Satisfaction
KPIs
- in-store experience
- value
Fill Treasure Chest
Length of Relationship
% Spend
Market Share
(KRA) Financial Performance
KPIs
- growth
- EPS
- EVA
- ROCE
- dividends

FIGURE 1.9.4 Example of a model for success. (*Adapted from Rucci, Kirn, Quinn, 1998* [4].)

Drivers and Enablers of Change

The work breakdown structure portion of the planning wall represents, as we have said, the work facing a top team and others in the organization needed to achieve the desired point of arrival. Inevitably, the work identified will be a mixture of what we call "drivers" and "enablers." The simple distinction is clarified in the following model (see Fig. 1.9.5).

Drivers are the actions that organizations take to bring about change. These actions have a direct causal relationship to the results the organization wants to achieve. Enablers are moderators or enhancers. They are factors that may not directly create the results you want, but that enhance the impact of drivers. They are an important facet of the conditions for success. Peter Senge, perhaps, has the best analogy for this [5].

> Gardeners succeed by attending to a host of conditions that could prevent growth from occurring. Success equals growth and yield (flowers, fruit, vegetables). Success is a function of good seeds, good soil, and good nurturing. The seed and the medium together must have the potential to produce the sort of reinforcing processes that lead to growth and yield. We all know how to support growth, and yet we typically operate in exactly the opposite ways in our organizations. Some leaders try to force growth by overemphasis on certain drivers instead of creating conditions for genuine growth and change. This is not a passive process. If anything, conversion to this point of view takes more work than commanding people to change.

So, at this point in the development sessions we operationalize the enablers by introducing the concept of fronts or subsystems. We present nine fronts for the consideration of the top leaders: planning, infrastructure, communication, measurement, technology, motivation, learning, culture, and politics. We suggest that the leaders make each of these fronts a row on the planning wall. We use the term "front" as a metaphor. In a war, there are typically multiple fronts. If one front gets too far out ahead of other fronts, the whole operation is at risk. If a front lags behind other fronts, the entire operation is at risk. So the goal is to maintain balance on frontal progress. In the gardening example, the objective would be to get the right amounts of light, nutrients, water, and temperature to create the optimal growing conditions. We find that many, if not most, organizations do not have balance across the fronts and that there are frontal lags that are hurting the organization's performance. Often, top leadership simply is not conscious about the yield loss. They may be stuck in their paradigms and don't understand the benefit-to-cost ratio for investing in selected conditions for success. They see it as an unnecessary cost without enough yield. When we get them to think about $6400 possibilities and then address what it would take to achieve the full potential, often they become more conscious or receptive to addressing other fronts such as measurement, planning, and communication. The development session with the top team provides the opportunity for

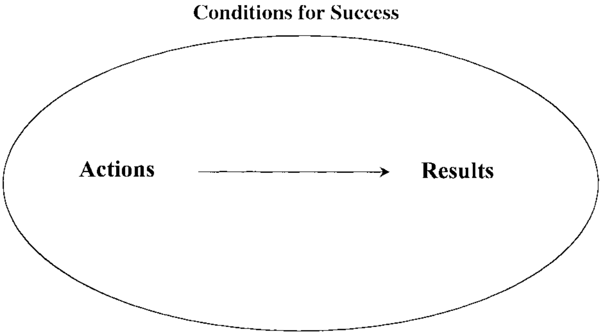

FIGURE 1.9.5 Action–result model.

them to get away from the action-result world of "A work" and "C work." We slow things down so they can examine their assumptions, their beliefs in cause-and-effect relationships, their strategies and actions in the context of what they want, and their requirements for success in the context of success as they have defined it.

The product (output and potential outcomes) from the development session is as follows: (1) a significantly enhanced definition of success; (2) a significantly improved understanding of the model for success; and (3) a reexamined set of strategies and actions. What is created is a completed planning path that is visible. The leaders can stand back from it and see the whole set of strategies and actions. This visibility is useful—it is rare that organizational grand strategies are laid out in this fashion. One of the better examples of a planning wall was created by the United States Postal Service. They have a large conference room in which the overall grand strategy fills the walls. The illustration we provide is a simple example of a planning wall to help you get a sense of the product (see Fig. 1.9.6). We reiterate our emphasis on the fact that the paper output is the booby prize in one sense. The outputs of any planning process must be instrumental to achieving the desired end outcomes. If the steps and outputs along the way don't do that, then you have to alter the steps and intermediate outputs to do this.

Perhaps the most important outcome of the development session is the degree to which each and every member of the top team becomes connected to the point of arrival and to the work that must be done to achieve that point of arrival. We have participated in many excellent development sessions, a recent exemplar of which were those with the Fleet Technical Support Office for the Atlantic Fleet. They had been chipping away at improvement for over ten years. At an offsite location in Williamsburg, we engaged them in a development session with 25 of their top leaders and managers. One outcome was that they revised their sense of what work would be required to achieve full potential as an organization. They also expanded the number of senior leaders engaged in the improvement activities from 25 individuals to 17 or so subteams of from 5 to 7 members, each one working on a different improvement project. This is their implementation and deployment phase of large-scale transformation. Another recent exemple comes from the Public Utilities Commission of Ohio (PUCO). They started when a half dozen middle managers attended a public offering of a planning workshop. Over a two-year period they migrated to a commission-wide involvement that engages literally hundreds of staff from every level in teams addressing dozens of aspects of the PUCO grand strategy. We cite these smaller and lesser-known organizations to highlight the fact that it isn't just the GEs of the world that are working on transformation and that smaller organizations don't have to adopt the complexity and magnitude of change that a GE undertakes. Transformation can be tailored to the size and character of the organization. There is no organization so small that it doesn't need to be thinking through revitalization.

Implementation and Deployment. Major changes like the ones that are started in development sessions with top teams evolve in the same way that processes do in nature, as Peter Senge [5] suggests. Just as in nature animal populations increase exponentially, in the same way one or two pilots or demonstration projects lead to four, then to 16, and so on. Each successive step in the exponential expansion springs from what was learned from past pilots. It's like our action research. We have a desired outcome, we understand the pragmatic first step, and we take it; we analyze what we have learned, formulate a logical next step, and take that; and so on. We go against the grain of the normal progression of events. We sometimes do pilots and then immediately expand systemwide. Senge goes on to address the need for understanding the forces that keep organizations from growing and improving. He suggests that 90 percent of effective leadership is commitment to address barriers to growth, such as fear, lack of trust, lack of feedback, and defensiveness.

Implementation and deployment throughout the organization is really a matter of harnessing the natural energy that people have for wanting to be part of a winning team. People want to succeed and they want to contribute. We begin with that assumption about people. Leadership's job is to define success, to develop the model for success, to build a game plan for succeeding, to get the right people in the right roles, to define the rules, and then to teach,

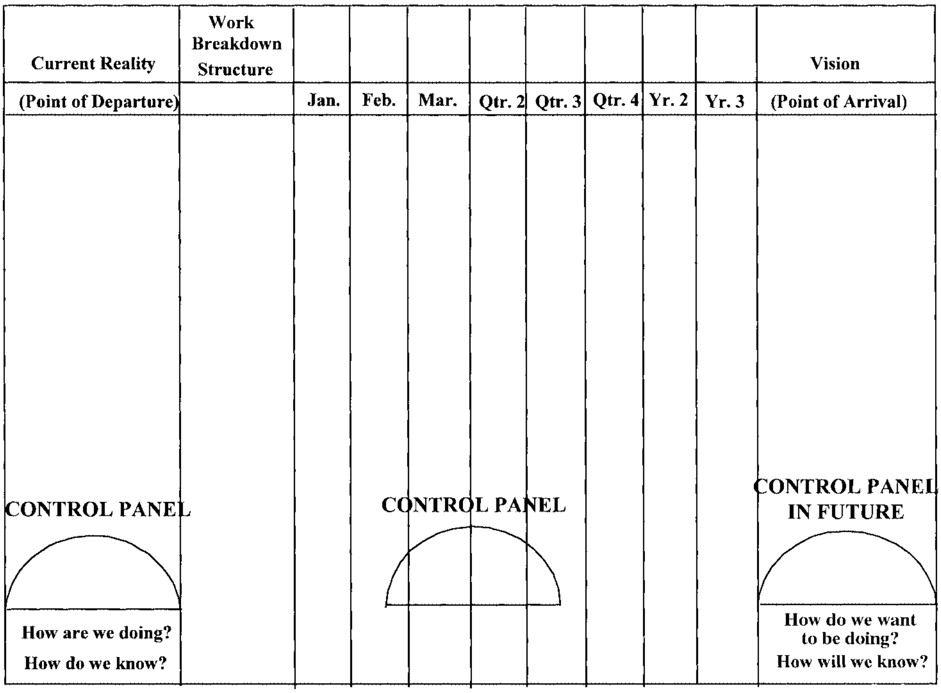

FIGURE 1.9.6 Planning wall model.

coach, and ensure that we execute over time. Once we have the work breakdown structure thought through—the game plan—it's just a matter of getting the right people to work on the right things.

We like to think about roles in terms of the functions of the architect and engineer (A&E), the construction management (CM), and the owner and operator (O&O). The development sessions put top leaders in the architecture and engineering role. They emerge from the session with a plan, a strategy, and planned actions, and they enter the construction management phase of transformation. Eventually, they will have created new, improved systems (e.g., measurement, planning, communication) and new, improved processes. The owners and operators then take over those new systems and processes. Our tactic is to have simultaneously created a new organization (new systems and processes) and a different set of operating conditions. Together, they represent the ingredients for moving toward full organizational potential.

Think about an ISE in the context of the three roles and phases of transformation (A&E, CM, and O&O). We'd suggest or contend that traditionally, in most organizations, an ISE is rarely involved in A&E, and is most often involved in CM and O&O. What we are promoting is the ISE role and involvement in the A&E aspect of transformation. It takes a different kind of ISE to do this. Not all ISEs are capable of performing in this role. Those who are capable and aren't engaged in this role need to qualify themselves and then assert their potential. They must ensure that the ISE is a key player in this phase of transformation. The Council of Industrial Engineers (CIE) is an affinity group (collegial group of peers) and represents examples of ISEs who are often engaged in the A&E phase of transformation. This group of senior leaders, with ISE backgrounds, meets twice a year to benchmark around improvement efforts from member companies. The IIE (Institute of Industrial Engineers) participates with this group. These CIE members are evidence that what we are calling for is happening, but it needs to expand and accelerate. When this occurs, the ISE (function/role) will be much better positioned in the organization and our contributions will be better leveraged.

This chapter is not the forum to discuss all the fronts. Here are some examples of frontal work by ISEs as part of organizational transformation:

First, and perhaps foremost, there is a need for overall program management, for someone to oversee the entire grand strategy. The program manager must see the big picture, work closely with the top team, facilitate meetings, challenge the group, and keep the database current and well portrayed. We think that the ISE provides good background for this, particularly if he or she has an advanced degree that is more interdisciplinary in character and also has good interpersonal skills.

Measurement Front. What is needed here is to reengineer the measurement system. We know that what is measured has a profound impact on what gets attended to and, of course, on the results that are created. The linkage between the planning front and the measurement front is critical. This is why Kaplan and Norton [6] and others, in their work on the balanced scorecard, stress the relationships among strategy, policy, and measurement. Measurement systems should support decision making, problem solving, and opportunity capturing. Measurement should lead to effective execution of the study and act phases of the PDSA improvement process. Measurement systems should promote systems and statistical thinking. Our experience is that most measurement systems do not. This must be remedied in large-scale transformations and it must be done early on.

We believe that ISEs are uniquely prepared to lead such work. Their foundation in work measurement, statistics, accounting, engineering economic analysis, and operations research provides the analytical strengths to contribute to building effective measurement systems. The one challenge that ISEs face is being able to move from the individual work center or worker unit of analysis to the organizational system unit of analysis. Many ISEs do not have a design and development orientation for measurement. They were taught how to install standards, not how to build measurement systems.

The Management System Model (see Fig. 1.9.7) is useful for explaining the fundamental steps in building measurement systems.

The steps to designing and developing an effective measurement system are highlighted in this model. It begins with the development of a solid understanding of the organizational system that is being measured. The target might be the firm, a plant, a department or function, or a business process. Organizational systems analysis is the first step and has a number of substeps. Essentially, we want the leadership to develop enough insights to be able to build their model for success. Once this is done, the organization will have more focus in terms of what to measure. We recommend measuring the variables that drive the desired end outcomes. These measures reflect the right side of the model. (In the Sears example, the desired end outcome was be a compelling place to invest.) We want organizations to measure in a way that provides them with longitudinal or time series data. This creates the opportunity to begin to think statistically about variation in performance over time—to understand variation.

Next, the designer and developer of the measurement system should understand user struggles. What decisions is the user for the measurement system facing? What decisions aren't adequately supported by proper information? This is the decision-to-action interface in the model. We also want you to understand the user(s) themselves. Who are they? What are their portrayal preferences? What does their current measurement system look like? What satisfies and/or dissatisfies them? What information do they have that is useful? Do they have accurate cause-and-effect understanding? What information would they like that they don't have? What don't they need to measure (thus eliminating the noise from unnecessary measures so that the signal is more detectable)? Answering these questions requires understanding the user(s) and the information portrayal–to–perception interface.

At this point in the process, we usually find it is helpful to introduce some balanced scorecard insights to the measurement system user group. Normally, this would involve some education and training. We find that the books and articles on the balanced scorecard (e.g., [6]) and

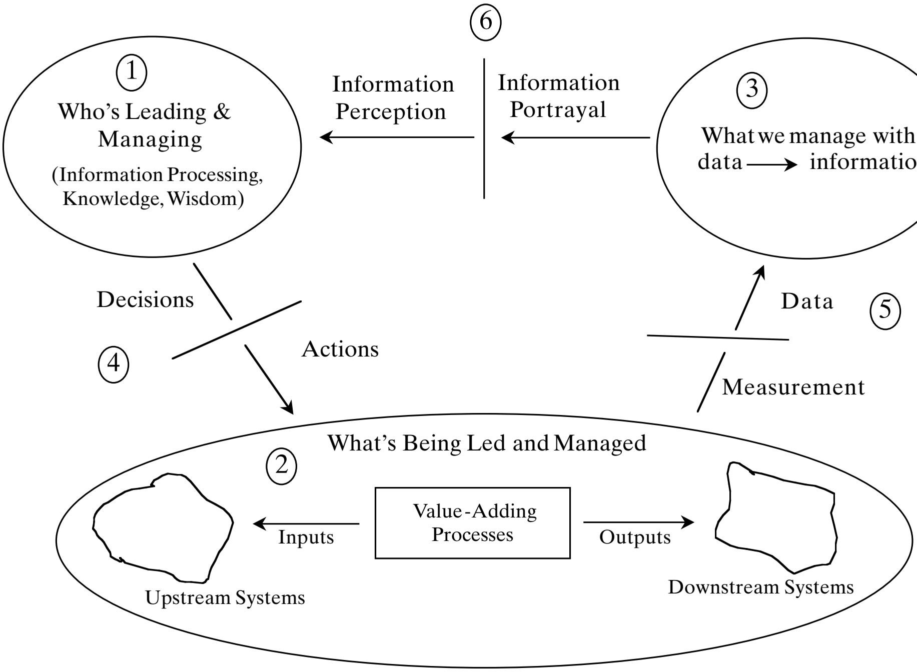
⑥
①
Who's Leading & Managing
(Information Processing, Knowledge, Wisdom)
Information Perception
Information Portrayal
③
What we manage with
data → information
Decisions
④
Actions
Data
⑤
Measurement
What's Being Led and Managed
②
Value-Adding Processes
Inputs
Outputs
Upstream Systems
Downstream Systems

FIGURE 1.9.7 Management system model.

the CD simulation are useful for this. The Sears article [4] also provides a tangible example that people can relate to. Another excellent article, also from the *Harvard Business Review,* is "Realize your Customers' Full Profit Potential" by Alan Grant and Leonard Schlesinger [7]. We use this foundational knowledge about measurement to guide the process of building a prototype chartbook. It begins by first assembling information that is available currently from the system and putting it in one place. We analyze the balance, the portrayal quality, the gaps, and the relationship to the model for success. We add, modify, and/or delete the key performance indicators in the chartbook to achieve balance. This normally takes several months and many iterations or versions. Once we get a version that is satisfactory, we train the users and user team in how to use a chartbook to effectively execute the "study" and "act" processes. This requires stopping certain less useful habits and starting certain new, useful habits. It is habit-breaking and habit-establishing. This takes some time, as well as coaching. The ISE can and perhaps should lead this development process, along with others. We rely heavily on key people from Information Systems, Organizational Development, and also from Finance, teaming with them in this effort. This is about building systems and statistical thinking into the reengineering of measurement systems. Again, we think that ISEs are naturals for this.

Culture Front. Culture consists of shared values, beliefs, attitudes, and norms. Schein [8] formally defines it as "a pattern of shared basic assumptions that the group has learned as it solved problems of external adaptation and internal integration, that has worked well enough to be considered valid and, therefore, to be taught to new members as the correct way to perceive, think, and feel in relation to those problems." Often, we find that the shared values, beliefs, and attitudes are not supportive of achieving full potential, of being a $6400 organization. We compare and contrast typical attitudes and behaviors with full potential attitudes and behaviors in Fig. 1.9.8.

THE ROLES OF INDUSTRIAL AND SYSTEMS ENGINEERING IN LARGE-SCALE ORGANIZATIONAL TRANSFORMATIONS

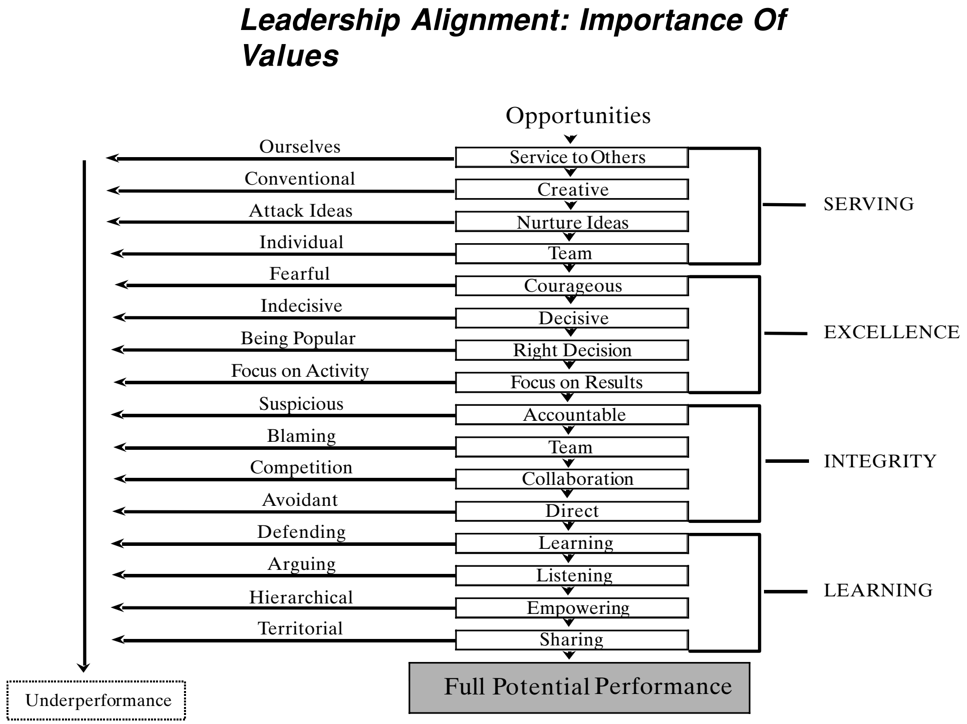
Leadership Alignment: Importance Of Values
Opportunities
Ourselves
Conventional
Attack Ideas
Individual
Fearful
Indecisive
Being Popular
Focus on Activity
Suspicious
Blaming
Competition
Avoidant
Defending
Arguing
Hierarchical
Territorial
Service to Others
Creative
Nurture Ideas
Team
Courageous
Decisive
Right Decision
Focus on Results
Accountable
Team
Collaboration
Direct
Learning
Listening
Empowering
Sharing
SERVING
EXCELLENCE
INTEGRITY
LEARNING
Underperformance
Full Potential Performance

FIGURE 1.9.8 Leadership values model.

Attending to the culture front involves creating a culture that will support the organization's achieving full potential. You cannot just accept the culture you have. We promote taking proactive steps to create a culture that will support the planned transformation. This front is obviously very critical. It is an example of a front that most ISEs are not competent, trained, or skilled at working on. While working to acquire the requisite knowledge, we specifically have sought outside assistance with this front. We, as ISEs and a part of the architecture and engineering team, have worked closely with outside experts to ensure that our clients' culture front strategies and actions were aligned with the other initiatives.

Technology Front. We define the term technology very broadly. By it we mean, "the way things get done." Technology in this broad sense, then, can be hardware, equipment, software, methods, procedures, policies, processes, and so forth. Clearly, this front involves mainstream ISE skills. The biggest challenge on the technology front is to establish process thinking—to get people to understand business processes and systems/front work, achieve some early successes, establish process measurements for baseline information, and shift mindsets from a functional orientation to a horizontal process orientation with a view toward succeeding at the model for success. A business process begins and ends with the customer. There is a series of actions that must occur in between the customer exchanges to ensure that the organization is a compelling place to shop. We encourage organizations to continue to work to optimize these steps so that they become a compelling place to invest. This requires thinking about the whole set of steps, not just portions of it. Most organizations, even today, still suboptimize pieces or chunks of business processes.

The actual technical aspects of process improvement are well supported with materials, training, examples, and the like. An example would be value stream mapping from Rother and Shook's *Learning to See* [9]. It's basically process mapping, only at the enterprise level.

The mental shift to the enterprise level of systems thinking and the change management implications is the toughest aspect for ISEs. So, although ISEs are the right resource for this front, the specific challenges the front presents are more change management in character than solution delivery. Getting the process right—making it better—is relatively straightforward. Getting people to behave according to the new process is the bigger, tougher issue. This raises another area in which ISEs need to expand their expertise.

Communication Front. The communication front has to do with the system for sharing information. This front is highly interdependent with the learning front and the infrastructure front in this respect. In *High-Involvement Management,* Ed Lawler [10] suggests that in order to be more effective, organizations need to share information, then knowledge, then power, and then rewards, in that order. In our front language, this would translate to working the communication front, then the learning front, then the infrastructure front, and then the motivation front. (Remember, infrastructure is how you are organized to perform and improve; it includes the empowerment issue and the decision-making, problem-solving, and creation processes.)

Here again, we don't think that ISEs are uniquely trained to actually work the communication front; however, they do need to be involved in the improvement of the front and to be aware of its importance relative to other fronts. One "heads-up": Many leaders we encounter have a need for control. They actually prefer to withhold information. They share information only on a need-to-know basis. This is the culture in many organizations. We are arguing for more balance in their viewpoint and in their actions. We're not suggesting that informed workers will necessarily perform better. We do believe that employees are generally underinformed about the organization, their work performance, their subunit's performance, and so forth. We do know that knowledge of results (KOR) is a very powerful known motivator of human performance.

To enhance communication, we advise that shift meetings, period end meetings, all-hands meetings, monthly leadership team meetings, and quarterly review sessions be built directly into your transformation efforts. You won't necessarily end up with more meetings, you will end up with more effective meetings (from the standpoint of information sharing and involvement). Meeting management is a key to being successful with this front. Most information sharing happens in meetings. If meetings are managed poorly, then you end up hurting your performance. If meetings are managed well, with the end in sight and with disciplined execution, then you can end up enhancing your performance even though you are taking time away from work. Information sharing and dialogue in meetings becomes more formal, and day-to-day interaction and the "grope time" are probably more powerful; hence, there is a strong connection between the culture front and the communication front.

Planning Front. The next front we will address is the planning front. Again, we feel that reengineering is necessary here. We encourage rethinking how you plan, who is involved in the planning effort, how plans are used, and how they are promulgated/communicated throughout the organization. The planning process is a subcomponent or a subprocess of the improvement cycle. Simplistically, the improvement cycle is the Shewhart/Deming plan-do-study-act cycle. The contribution of the planning front–system is to ensure that planning for improvement is going on in an integrated fashion throughout the organization. Strategy and policy formulation leads to implementation and deployment. Three-level meetings, for example, are mechanisms or steps in the process that lead to information sharing about the plans and strategies, two-way dialogue (top-down and bottom-up), knowledge and skill sharing relative to effective implementation, recognition of successes, and so on. The point is that planning isn't the end, the creation of a plan isn't the end. Getting the desired results is the end, driving improvements against the model for success is the end. If the way you currently plan doesn't lead to effective implementation and deployment, then you need to change how you plan. Reengineering of planning needs to be done in most organizations today.

The ISE is not necessarily knowledgeable, skilled, or practiced at planning from the perspective we describe. Additional assistance is often required and the internal ISE should be an integral part of the work on this front. Planning needs to be integrated and aligned across all levels. Plans for improvement in a work center or function need to be understood in the context of the system. "B work" (building the business, improving performance) should be an accountability at all levels of the organization and it needs to be coordinated. That's what the planning front is all about.

Infrastructure Front. The infrastructure front represents the system that determines roles, responsibilities, and accountabilities for "A work," "B work," and even "C work" (again, running the business, building and improving the business, and fighting fires or catering to crises—see Fig. 1.9.1). How are you organized to do "A" and to do "B" and even to do "C"? Are you organized effectively and efficiently? Transformation focuses mostly on establishing an effective infrastructure for doing "B" and ensuring that it works well with the "A" infrastructure (traditional organization chart). The issue of whether there should be parallel or shadow infrastructures is an open question. Ideally, we'd like the "A-work" infrastructure to be effective and efficient. We also want leaders and managers who play roles in the "A" infrastructure to be also accountable for "B work." In all honesty, this doesn't often happen. So, we find it necessary to create ad hoc process improvement teams that are staffed cross-functionally with the aim of improving things.

One additional aspect of infrastructure is the creation of positions known as "front owners" and "business process owners." For example, it is common that no one owns the communication system or the measurement system or even the technology system. These important functions are either not led and managed or they are assumed to be delegated to functional subunits of the organization. Just as organizations found when they began to do reengineering, no one really owns fronts and business processes. For example, who owns the supply chain management business process in your organization? Often, the answer is no one single person. Pieces of processes are typically owned by functional leaders. This leads to suboptimization—that is, optimization of the parts and suboptimization of the whole.

So, we encourage the designation of front owners—individuals who will take charge of the design, development, and implementation of an improved, corporatewide, and integrated measurement system.

PUTTING IT ALL TOGETHER

Transformation involves radically changing the capability of the organization to perform, to innovate, to survive, to thrive, and to sustain. It's about moving the organization toward $6400 status—full potential. You can muddle your way along in a piecemeal fashion and simply not get the job done. Or, you can tackle this like a big project or process/system and systematically work toward the desired end. It's a matter of being clear about what you want and of making choices accordingly. Are we suggesting that every leader of every organization should work to achieve full potential? Not really. It's not our role to form judgments about those choices. Being a $1000 organization and having survived for 70-plus years isn't bad or wrong. The question remains, What was possible? It depends on what you want. If, however, you choose $6400—full potential—and your strategies and actions do not add up, do not make sense, or are not compatible with that choice, then we think you have to be intellectually honest with yourself and about your true intentions. Our intention is to partner with organizations. We look for leaders who opt for full potential and work with them to achieve that.

SPECIFIC EXAMPLE

The authors have been heavily involved in a number of large-scale transformations in the past 10 years. We integrate our experience and learnings from these to provide an even more specific understanding of what large-scale transformation entails and also how ISEs fit in. Transformations require strong, powerful visions. It is not enough for one senior leader to have and hold the vision, there has to be a critical mass (coalition) of leaders who are aligned and attuned to the vision. Here is an example of such a vision.

Transformation Point of Arrival. We will invent a way of running the business built around maximizing the cash flow from current and potential customers (we will be a compelling place to shop) and in doing this we will continue to be a compelling place to invest. Achieving these two things will require that we be a compelling place to work (a form of investment). As we continue to get better at managing these relationships (between providers, employees, investors, and customers), we will continue to outperform our market and will survive and thrive. Figure 1.9.9 depicts the system of relationships we will work to optimize.

Specific programmatic initiatives that we choose to work on in order to optimize the relationships in this system (as depicted in the previous figure) are as follows:

- Customer relationship process optimization (examples include customer segmentation; tailoring of offerings; customer base management process; category management process; in-store interactions; customer satisfaction measurement system; and customer-driven attitudes throughout business)
- Optimization of business processes that provide valued products and services to our customers (supply chain management; retail operations management; perishable quality

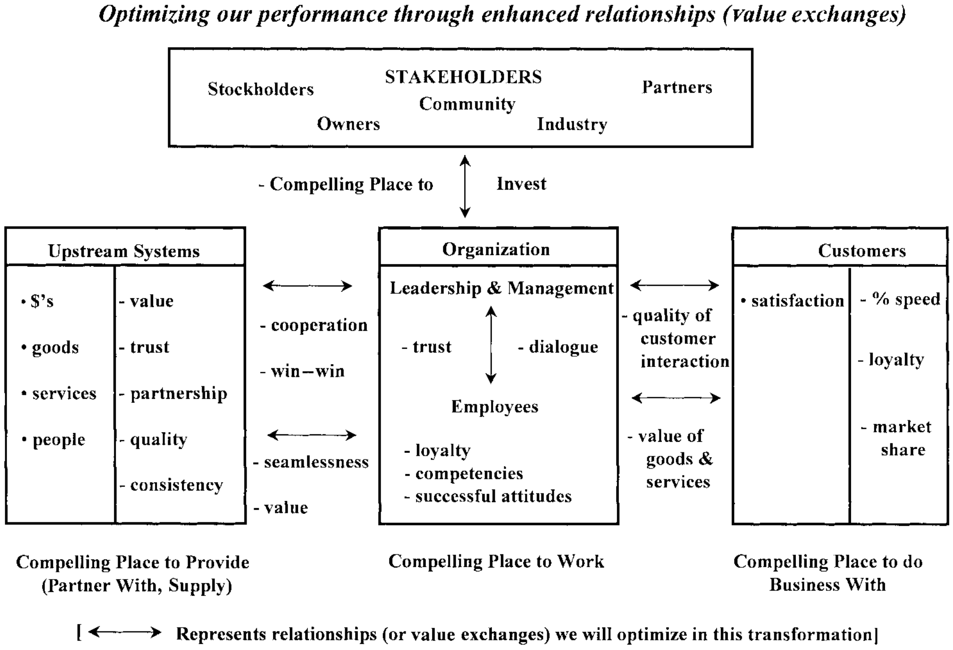
Optimizing our performance through enhanced relationships (value exchanges)
STAKEHOLDERS
Stockholders
Community
Partners
Owners
Industry
- Compelling Place to
Invest
Upstream Systems
• $'s
• goods
• services
• people
- value
- trust
- partnership
- quality
- consistency
- cooperation
- win—win
- seamlessness
- value
Organization
Leadership & Management
- trust
- dialogue
Employees
- loyalty
- competencies
- successful attitudes
- quality of customer interaction
- value of goods & services
Customers
• satisfaction
- % speed
- loyalty
- market share
Compelling Place to Provide (Partner With, Supply)
Compelling Place to Work
Compelling Place to do Business With
[←→ Represents relationships (or value exchanges) we will optimize in this transformation]

FIGURE 1.9.9 Conceptual model for vision.

management; corporate services management; information systems management; and buying/sourcing management)

- Organizational capability (roles, responsibilities, and accountabilities; competency building and retention; performance management process; learning, knowledge, and skills enhancement; personal and professional mastery; and engaging employees in "B-work")
- Leadership and management alignment and attunement (focused business purpose; shared values and operating principles; results-oriented executive mindset; sense of urgency versus sense of emergency; improved understanding of market; understanding of what it takes to be "built to last" ($6400) and also what it takes to be a "living company"; integrated strategic, operational, and financial strategies and approaches; and enhanced team work when appropriate)

These four major categories of activities became the implicit strategy and set of actions that the leadership committed to for successful transformation to the vision as articulated previously. It may be clear to the reader where and how the ISE role fits in even at this high level of strategizing, optimization of business processes being perhaps the most transparent at this point.

Large-scale transformation represents a commitment of resources and time. It requires program management knowledge and skills, as contrasted with project management knowledge and skills alone. Think of the Space Station as a program and one Shuttle mission as a project. Or think of building a factory as a program and site preparation as a project. It's a size, complexity, and interrelationship issue that differentiates the two types of tasks—program versus project management. Being able to translate the vision into chunks of work that have to be done is really an art form. It requires being able to blend specific things that need to get changed in the organization in order for it to perform better—for example, reengineering the supply chain (which in and of itself would have to be broken down into projects) or changing leadership understanding. Our change model suggests that readiness for change is a function of three things: shared understanding of the vision; intention, desire, and need for change (desirability of the vision and/or burning platform); and clearly understood first steps. These three things are in a mutual relationship with one another. In other words, if I have low shared understanding of the vision, then I get low support for change. All three have to be addressed.

In recent experiences with transformation, we felt we had a powerful vision. We felt the reason/rationale/motive for change was understood, at least at the top of the organization, and this left working on clearly understood first steps. At this point, many leaders and managers are overwhelmed. They see the future—they have a sense of it—and yet they don't clearly see how to get there. So, the ISE role, in our example, is to map out even more specific strategies and actions (programs and projects and activities) that will begin to move us toward the vision. It's just a process of thinking it through and mapping it out.

Conceptually, we broke the transformation into stages or phases. We wanted to build consensus and understanding with top leadership, build our model for success, create the logic for the transformation approach, and get it sold. Then, we wanted to experiment, to do detailed design and development work, and to do pilot testing and demonstrations. This would continue to build understanding and confidence in the approaches being put forward. In stage 3.0, we wanted to build new capabilities in the organization for the new processes and attitudes, and for the different relationships with employees, customers, providers, stockholders, and stakeholders.

What we've done in Fig. 1.9.10 is to actually show you the stages of transformation. Each of the five rows is a major programmatic effort (as we discussed above) and would show up on the middle of the planning wall mentioned earlier. The columns correspond to units of time for the transformation. The total transformation might take 3 or more years; many of the large projects or programs (such as supply chain reengineering) might take multiple years in and of themselves. Significant gains in performance can occur almost immediately, and performance will improve over time throughout the transformation. A word of caution: Low-hanging fruit gets picked early in the change process. It is unrealistic to expect the early rate of improvement will be sustained unless energy expenditures are managed carefully and top leadership stays the course when things slow down and achieving results becomes more difficult.

	1.0 Build Consensus	2.0 Design/Develop/Do Pilots	3.0 Build Capability/ Deploy	4.0 Stabilize
Transformation PDSA (Plan, Do, Study, Act)	• form strategy team • engage senior leadership • strategize • create Grand Strategy	• Grand Strategy promulgated • Point of Arrival description • do pilots/demos	• build policy deployment strategy • gain leadership support • effective PDSA on the initiative	• visualization of next 5-7 year development/ implementation program
Leadership & Management Learning & Development	• create alignment & attunement • strategy & policy formulation • personal mastery (top 2 levels of leadership)	• ownership/sponsorship of pilots • stay engaged in Grand Strategy development & early execution	• active involvement in expansion • continued learning • partners with Strategy Team	• high performing individuals & teams
Organizational Capabilities	• assessment • prioritization	• roles/responsibilities/ accountabilities • learning front emphasis focused on behaviors that optimize	• deploy improvement cycles • learning continued • realign skillsets	• learning organizational characteristics
Optimization of Business Processes & Positioning	• assessment • prioritization • model for success	• repositioning decisions • value stream mapping • methodologies established	• core process reengineering • new business ventures	• innovation habitual • market share, customer loyalty & profits significantly improve
Relationship Process Optimization	• assessment • prioritization • research/modeling	• pilot testing/validation • learning from customer-driven perspective	• relationship process optimization	• way of doing business, standardize

FIGURE 1.9.10 Transformation overall approach model.

During transformation, an ISE can play many roles. To portray this, we use what we call a stop sign model (see Fig. 1.9.11) to reflect the technical competencies of ISEs that can be brought to transformation and to an organization.

Match the sides of the stop sign model to the bullets under the five areas of transformation and to the stages in the transformation approach. This should give you a sense of not only the role and activities of ISEs in transformation, but also their timing.

BENEFITS

The potential benefits from doing transformation in a more systematic, integrated, and strategic fashion are significant. We know and believe from personal experience that the gains will be in the double-digit range, and could surpass that by an order of magnitude. In one initiative we were involved with, profitability increased by close to 1000 percent and stock prices rose 5½ times what they were when the transformation began. Surveys indicated that employees sensed organizational progress in "walking the talk" (behaviors becoming more aligned with stated values). Also, the supply chain was reengineered, an improvement in productivity of close to 40 percent was achieved and sustained, balanced measurement systems were institutionalized, data-driven decisions became the way business is done, and improvement cycles were established and continue to grow. The fundamental question is whether the people who are the organization are connected to the possibilities and are mobilized and energized to capture the opportunities that are available. If that result or benefit is achieved, then bottom line results will take care of themselves.

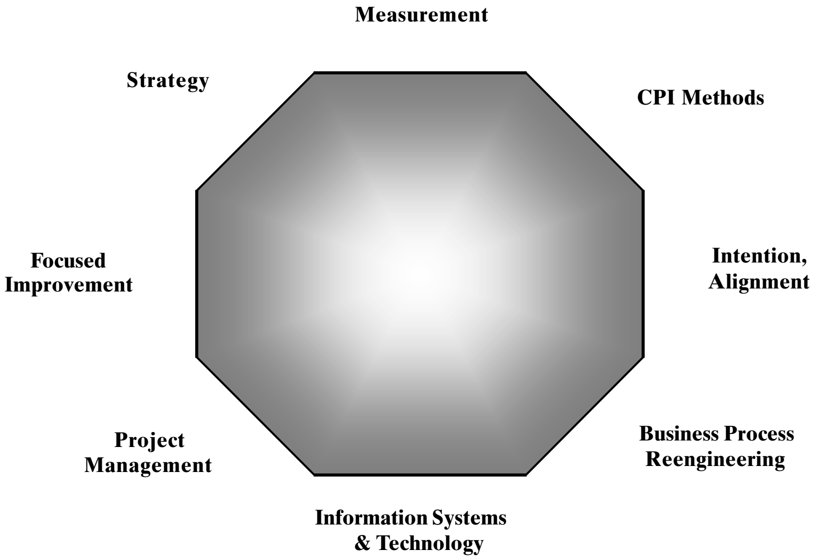

FIGURE 1.9.11 Organizational transformation intervention model.

Benefit/cost analyses for efforts like this are tough to crystallize. Most leaders don't make a decision to take on projects of this magnitude on the basis of a benefit/cost ratio. They are more likely to act on a belief that it is the right thing to do. This is what separates leaders from managers. The late Bart Giamatti, former President of Yale University and, after that, Commissioner of Major League Baseball, said it well: "Management is the capacity to handle multiple problems, neutralize various constituencies, motivate personnel, and hit a budget or at least break even. Leadership is the moral courage to assert a vision of the organization in the future and the intellectual energy to persuade the community or the culture of the wisdom and validity of the vision." The quantitative numbers are not really that important, at the outset. Farmers don't need a benefit-to-cost analysis to know that water and fertilizer and weeding are essential to growth. They might analyze alternative fertilizers, but they would never not fertilize. We contend that many leaders choose to not fertilize and water—that is, provide the right conditions for improvement.

CONCLUSIONS

We believe that the large-scale transformations are a trend that will continue. Industrial and systems engineers have the capability to contribute in many ways to these large, complex, dynamic initiatives. Ideally, senior ISEs are an integral part of the architecture and engineering team and, of course, are integral to the construction management team and process too. There is an emerging science to these transformations. We know how to lead them and guide them—navigate through the permanent white waters of change that we experience. Our experiences are but a sampling of insights that exist out there today, and we encourage you to explore them. Seeing how you can be a part of something of this magnitude can be rewarding. Preparing yourself to be a leader and/or key participant in these efforts is important to your career development. It's a matter of choice—your choice.

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BIOGRAPHIES

D. Scott Sink, Ph.D., P.E., is in a learning leadership private practice focusing on the areas of performance improvement, strategic performance improvement planning, measurement, improvement cycles, change leadership and management, quality and productivity improvement, and large-scale organizational change. Scott served as a professor in Industrial and Systems Engineering at Oklahoma State University and Virginia Tech for 20 years (1978–1998).

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David F. Poirier, P.Eng., P.Log., is currently executive vice president for the Hudson's Bay Company in Toronto. Dave is an accomplished, results-oriented executive in the retail industry, with extensive knowledge in strategic planning, cost control and management techniques, distribution and logistics, procurement, and information systems. He is team-oriented leader with creative and dynamic skills in developing a strategic management process, complete with operational, organizational, financial, and human resource perspectives, combined with the operational skills and experience to run multiple divisions in a complex and fast-paced environment. He is a past IIE board member, past recipient of the Outstanding Young Industrial Engineer Award, and currently chairman of the Logistics Institute in Canada and a member of the Council of Industrial Engineers.

George L. Smith, Ph.D., P.E., is engaged as a private consultant working with corporate executives, their management teams, and their in-house staff supporting their initiatives in organizational transformation. Areas of support include performance improvement planning and implementation, creating and using balanced scorecards, change management, and large-scale change. Smith served as a faculty member in Industrial and Systems Engineering at the Ohio State University for 27 years (1968–1995), and has continued to teach as an Emeritus Professor. He has been named a fellow of the Institute of Industrial Engineers, the Human Factors and Ergonomics Society, and the World Academy of Productivity Science. He was president of the Society for Engineering and Management Systems from 1997–1999.

SECTION 2

PRODUCTIVITY, PERFORMANCE, AND ETHICS

Source: MAYNARD'S INDUSTRIAL ENGINEERING HANDBOOK

CHAPTER 2.1

THE CONCEPT AND IMPORTANCE OF PRODUCTIVITY

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Productivity is generally considered to be the ratio of output to input. The concept is simple, yet the ability to measure and analyze productivity often proves to be elusive. Historically, it has been the variety of input that has made it difficult to develop a meaningful measure. Today, we realize that the output side of the equation may be even more difficult. We cannot simply produce for the sake of producing, but rather must produce to meet customer needs. Those needs reflect not only quantity, but also quality and time of delivery.

The potential complexity of the equation may discourage us from even attempting to measure and analyze productivity. However, a common understanding that it is improvements in productivity that lead to increases in our standard of living will always cause us to be interested in measuring productivity.

This chapter reviews the concept of productivity, why it is so important, and how industrial engineers can impact it. Several chapters throughout this handbook address the specifics of measurement and analysis. The goal of this chapter is to provide a foundational understanding of productivity on which you can build your improvement plans.

PRODUCTIVITY DEFINED

Productivity generally expresses the relationship between the quantity of goods and services produced (output) and the quantity of labor, capital, land, energy, and other resources to produce it (input). When measured, productivity is often viewed as a relationship between output and a single measure of input, such as labor or capital. When there are multiple input measures or indices, the equation becomes very complex, often requiring subjective weightings. This is where the seemingly simple definition of output versus input becomes complex and confusing.

The understanding of productivity has been further complicated by a growing realization that simply producing effectively does not necessarily mean one is productive. One must be producing what the marketplace needs, when it needs it, and at a competitive price. The ideal of meeting customer needs and expectations without error or waste has now entered the equation. This suggests that anything produced that the market does not want cannot be considered an output when calculating productivity. So now the output side of the calculation is also complex.

An example of this growing complexity can be seen in an examination of labor productivity. Industrial engineers have often placed most of their focus on the input. When considering labor productivity, the input is simply the quantity of labor expended. In a more sophisticated analysis, the industrial engineer will also consider things such as how effective the labor is by measuring performance, utilization, and method levels.

Even with this level of sophistication, the industrial engineer has typically only considered the value of the parts produced or the total standard hours produced as the output. The parts produced might sit in inventory, be sold at a discount, or may never be sold. Unless more attention is given to the output, making sure what is produced is meeting a customer demand, the industrial engineer will only be helping to improve the production of waste.

The definition of productivity must always reflect a comparison of output to input. The details of the definition depend on what is considered output and input. There is no perfect definition to suit each situation. The definition an organization uses should be a direct reflection of the purpose for making the measurement. In many cases, the purpose of making the measurement is to benchmark improvement. If that is the case, then the definition should reflect the organization's measures of success. For example, if profitably delivering flawless products to the customer in a timely manner at a competitive price is considered success, then the organization's definition of productivity should reflect each aspect of that statement. Once the definition is constructed and productivity is measured, then the organization may use it to benchmark improvement and to analyze deficiencies.

WHY PRODUCTIVITY IS IMPORTANT

Real gains in productivity are more important than simply measuring success in meeting objectives. Improvements in productivity have a significant impact on lives whether the change occurs at the national level, within a given industry, for a particular company, or even on a personal level. In many cases it is the standard of living enjoyed by those involved that is impacted. On a national level, productivity is often discussed in the media as a measure of a country's increasing prosperity. As a nation becomes more productive in the use of available resources, it experiences growth. Growth leads to improved products and services, increased consumption, and more leisure time. The increases in productivity brought about by new technologies introduced in the late 1900s certainly have had a significant impact on the standard of living in many nations. Figure 2.1.1 shows the direct relationship between productivity and compensation on a national level.

Changes in productivity within an industry or at the company level are closely related to success and survival. The profit margins realized by an industry or a specific company are directly related to its ability to make productivity gains ahead of the competition. Industries where competition helps propel improvement often experience greater growth. Companies that fail to keep pace will fail. In either case, all stakeholders are directly impacted.

Personal productivity has become of greater interest to many individuals. Whether driven by the search for self-fulfillment or by the ambitions of success, many people are actively seeking the means to improve their own productivity. It is understood that it is the productive individual who receives opportunities on important projects or advancement within the organization. Complete industries are emerging to help individuals improve their personal productivity through training and technology. As might be expected, the desires for individual productivity improvement are generally personal.

In reality, it is the sum of the individual improvements that lead to a synergy of higher-level advancements, ultimately resulting in higher national productivity levels. As individuals we certainly can improve our own situation by increasing our productivity. However, we should not lose sight of the importance we can have on improving the productivity of the organization, or the industry, in which we work, or the nation in which we live. Our successes can have a positive impact on the standard of living of others.

THE CONCEPT AND IMPORTANCE OF PRODUCTIVITY

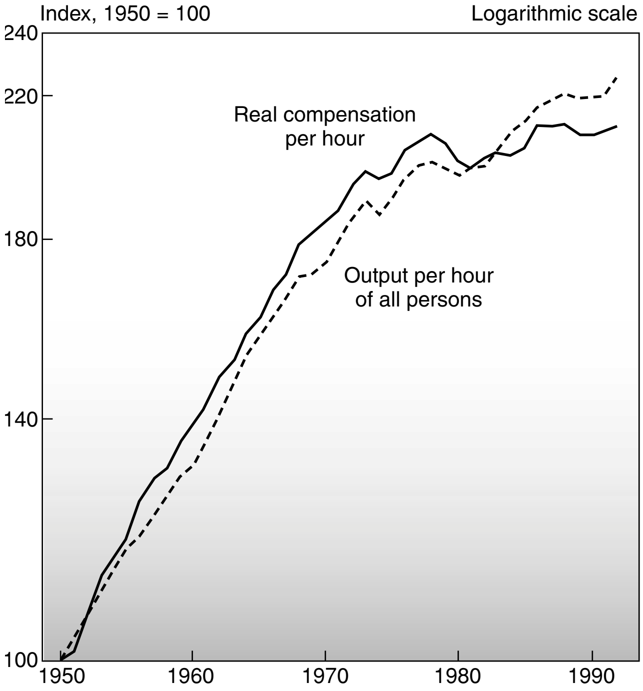

FIGURE 2.1.1 Output per hour of all persons and real compensation per hour in the business sector from 1950 to 1992. (*From the Bureau of Labor Statistics.*)

THE INDUSTRIAL ENGINEER'S PERSPECTIVE ON PRODUCTIVITY

In the past, the mission of industrial engineers has generally been to increase the output of all of the available resources. As industrial engineers, we worked to maximize machine utilization. We suggested layout and method improvements that would allow the worker to produce more. We established engineered labor standards to support individual incentive programs that rewarded workers for producing as many quality parts as possible. The assumption was that increased output meant increased productivity.

The shift from mass production concepts to lean production during the 1990s has helped to refocus the industrial engineer's role. Many of the tools remain the same, but the context in which they are applied has changed. Rather than simply improving operations to produce more effectively, industrial engineers must first understand the customer's demands, then work to determine the most effective manner in which to meet them. With lean production the focus is on doing everything better, faster, and cheaper—delivering the product the customer wants, when they want, and at a competitive price. The industrial engineer must now focus on value-added activities and the elimination of waste.

The title *industrial engineer* implies an association with manufacturing or production-type operations. This too is changing as companies recognize the importance of viewing productivity from a more holistic standpoint. To simply improve the labor productivity in a manufacturing operation with little or no regard to the rest of the business will likely negate any possibility of actually realizing the benefits of the improvement. Overproduction is a simple example. Given this, the industrial engineer must have the latitude to assess the entire value stream, from order taking to shipment to collection of receipts, and then help to facilitate improvements that will enhance the flow of value to the customer.

The industrial engineer's perspective on productivity has been somewhat narrow, often focused on increasing output by improving labor productivity on the shop floor. This is changing. Now the industrial engineer must serve as productivity engineer. It is imperative that the industrial engineer understand the definition of productivity as it applies to the organization being served and diligently use the skills and talents he or she possesses to make improvements. Furthermore, the industrial engineer must become the champion of productivity improvement, helping others to understand the definition, the importance of making improvements, and how those improvements can be made.

MANAGEMENT'S ROLE AND RESPONSIBILITY

Peter Drucker sums up management's role quite well: "The primary reason management exists is to improve productivity." Drucker is not stating that management should support the occasional productivity improvement project. He is saying that it should be on the top of every manager's list. For an organization to survive, it must seek to continually improve productivity.

The important role management takes should be very encouraging to the industrial engineer in two ways. First, industrial engineers should feel assured that their efforts will always be supported by management. This may sound a little absurd, but consider this—if the industrial engineer is focused on making improvements to productivity, and the industrial engineer clearly understands the company's definition of productivity, then a manager who places productivity improvement on the top of the list has little choice but to support the industrial engineer's efforts. The only possible breakdown in the logic is with the manager's priority list. In that case, the industrial engineer must work to make sure the definition of productivity is clear and understood by all, including the manager.

Second, the industrial engineer should recognize that industrial engineering is an excellent stepping stone to management. Consider Drucker's statement again: "The primary reason management exists is to improve productivity." Since this is also the primary reason industrial engineers exist, then industrial engineering is obviously an excellent training ground for management. It also implies that industrial engineers will enjoy a close working relationship with management.

Both management and industrial engineers exist to improve productivity. Therefore, they must work closely together to ensure an organization's ultimate success.

THE KEY ELEMENTS OF PRODUCTIVITY

Organizations will achieve productivity gains in very different ways depending on their specific situations. Prior to discussing specific examples of measuring, analyzing, and improving productivity, it is helpful first to consider the key elements that impact productivity: inventions, innovations, investments, integrations, and information.

Inventions refer to creation of basic technologies such as the wheel, electricity, the engine, the telephone, the computer, and many materials. Inventions often introduce a much better way of doing something. Even though there are relatively few inventions, they can have a huge impact on productivity.

Innovations apply existing technologies to create new products or services. Innovations are much more prevalent than inventions. Examples include cars, refrigerators, radios, cameras, and so forth. Innovations often reflect the synergy of people building on and improving others' ideas. Consider the impact of the invention of the electric motor. While the motor by itself has no meaningful purpose, the innovative use of the motor in so many applications has had a significant impact on productivity.

THE CONCEPT AND IMPORTANCE OF PRODUCTIVITY

Investments are made when acquiring land, facilities, energy, equipment, tools, technology, and people. Resources, or input, are necessary to produce output. This particular element suggests that making the right investments is paramount to improving productivity. Making investments in resources that do not impact productivity is pure waste and should be easy to avoid. The more difficult task is selecting the investments that will have the most significant impact.

Integrations refer to the effective use of resources through the use of processes, work methods, layouts, systems, and so on. No organization can produce with only a single resource. Even in the rare case were only one raw material is involved in producing a product, people, equipment, and systems are likely to coexist. The effective integration of these resources can have a dramatic impact on productivity.

Information is the knowledge and data available to make the decisions necessary to produce. This includes education, communications, and databases. Whether decisions are being made by people, equipment, or systems, the information must be correct to be productive. Perhaps the best example here is the information regarding customer requirements. If the requirements are not made known to all concerned, then it is likely they will not be met.

Industrial engineers often have responsibilities that involve investments, integrations, and information—with a focus on integrations. An understanding of each element and a realization that they are interdependent will help the industrial engineer to be more effective in impacting productivity.

PRODUCTIVITY MEASUREMENT

The concept of productivity and productivity improvement is relatively straightforward. The measurement of productivity on the other hand is not. Whether measuring at the national, industry, company, or personal level, the number of possible factors and the weight of those factors introduce questions of accuracy and reliability. However, prior to judging the credibility of a productivity measure, one must first understand how the measure is being used.

Productivity measures may be used to measure the performance of an industry, a company, company management, or even a shop floor laborer. Companies may use measures to judge their competitive position. Investors may make their selections based on a productivity measure. Management and labor may be compensated based on a measure of their productivity. In many cases productivity measures are used as a benchmark to gauge improvement. Good measures will even help to identify issues or improvement opportunities. The important thing is that the measure appropriately reflect its intended purpose.

Probably the most familiar productivity measure to industrial engineers is that of labor productivity. Even this variation includes numerous possible factors. Maynard's approach to pure labor productivity includes a comparison of the standard hours earned to the actual hours required delineated by time working against standard, time off standard, and time not worked caused by significant delays. The result yields a measure of worker performance, utilization, and coverage. It assumes that the methods are reasonably good and that all of the resulting production is needed by clients. In an incentive environment the approach may be expanded to include a cost per standard hour calculation. This type of approach has served many companies very well who were in need of addressing labor productivity issues. It is, however, a very narrow measure of productivity.

Broader measures of productivity usually include a family of factors or indices. Each factor is weighted according to the relative importance it has in helping the organization meet its objectives. Possible factors in a manufacturing environment include

- Output per worker-hour (standard hours, value of product, number of pieces, etc.)
- Quality level (rejects as percent of output, audit score, etc.)

- Average production response time (lead time)
- Average level of work in process (WIP)
- Average hours of downtime per worker-hour
- Safety, housekeeping, and absentee indices

These are only a few examples covering a small portion of a whole organization. There are numerous other possibilities when indirect, office staff, engineering, and other parts of the organization are considered.

The same concepts apply to nonmanufacturing organizations. The example shown in Fig. 2.1.2 demonstrates how a productivity measure might look for a donut shop. The danger with the extensive number of potential factors is the very real potential of overcomplicating the measure. No organization should set up an elaborate productivity measurement system and anticipate substantial improvement unless they intend to work concurrently on improving

Company Mission

To serve customers first-quality donuts at a reasonable price in a timely fashion.

Objectives

Produce first-quality products.
Price products to be competitive with local bakeries and donut shops.
Fill customer orders quickly (from “hello” to “have a good day”).
Minimize wait time (standing in line).
Eliminate balking (line is too long to wait).
Make efficient use of space, equipment, and labor.
Minimize the number of donuts requiring disposal.
Eliminate order errors.
Maintain a clean, safe, and orderly shop.
Maintain accurate inventory records.
Minimize employee turnover.
Make a reasonable profit.

Potential Measures

Labor cost per sales dollar.
Average order cycle time.
Sanitation ratings.
Safety ratings.
Absenteeism.
Employee turnover.
Customer satisfaction.
Profit per square foot.
Value of product disposed per dollar of sales.
Sales dollars per square foot.

Selected Measures and Weightings

Labor cost per sales dollar	30 percent.
Average order cycle time	20 percent.
Customer satisfaction	30 percent.
Sanitation ratings	10 percent.
Employee turnover	10 percent.

FIGURE 2.1.2 Sample productivity measure for a donut shop.

their operations. Furthermore, unless every aspect of an elaborate system positively impacts productivity, the system itself may lead to a reduction in overall productivity.

In the end, it is imperative that each organization develop a productivity measure that best reflects its definition of productivity and objectives for improvement. The measure should be simple, easy to understand, clearly related to productivity objectives, and fully supportive of the purpose for the measure. Refer to Chaps. 2.2, 2.8, and 2.11–2.13; Chap. 13.7; and Chap. 17.11 for further examples of productivity measurement.

PRODUCTIVITY ANALYSIS

The first step in analyzing productivity is having a clear understanding of productivity and how it is defined and measured by the organization in question. In the event that no measure exists, the focus must be on how the organization defines productivity. It is not likely that this definition is posted on the wall. However, for organizations to survive, they must be making some efforts to improve the ratio of output to input. These efforts are the result of how they view productivity and what it takes to improve productivity. The initial analysis should question and test the validity of the organization's understanding and definition of productivity. This effort in itself will reveal significant information about the productivity of the organization.

Once the organization's view of productivity is understood, then further analysis can be completed. A thorough review of existing productivity reports can be made if a good measurement system is in place. If a measurement system is not in place, then a productivity assessment or audit must be conducted.

When conducting a productivity assessment, it is essential that the analysis again give full consideration to the organization's definition of productivity. There are a variety of tools for conducting assessments and the tools selected must be appropriate. For example, if asked to help assess the productivity of the direct labor workforce, Maynard uses a comprehensive approach that considers the performance (skill and effort) of the workforce, utilization, and the work methods and layouts. All supporting systems including pay systems and indirect support would also be reviewed. The result of the assessment would include a measure of how productive the workforce is compared with what should be expected in that environment. This type of analysis can be very useful in identifying specific problems with labor productivity. However, it may not be at all appropriate in an environment striving to integrate processes to better match production with customer demand.

An organization focused on lean production, for example, will include in their definition of productivity the desire to meet customer demand with as little waste as possible. In this scenario, the productivity assessment should be focused on the value stream. Maynard uses value stream mapping to help organizations better understand their current state of productivity and the opportunities for improvement.

Productivity analysis is really just the regular review of the organization's definition of productivity and an assessment of progress. If a reporting mechanism is in place, then it should be reviewed regularly. If there is not a reporting system, then industrial engineering should be tasked with conducting meaningful assessments on a regular basis. Refer to Chaps. 9.3, 9.6, and 9.7, and Chap. 16.2 for further examples on productivity analysis.

PRODUCTIVITY IMPROVEMENT

The result of productivity analysis should be a clear picture of improvement opportunities. The level of management attention to productivity will dictate the type of improvement program required. If little attention has been given to productivity, then management must evaluate the business planning process and be certain that productivity improvement is clearly reflected in the mission and vision of the organization. In a more productivity-conscious organization, the structure will be in place to continuously improve. Productivity improvement should be viewed as an ongoing, continuous process.

This handbook includes numerous chapters on different types of productivity improvement programs. The key is selecting those that clearly support the organization's understanding and definition of productivity.

FUTURE TRENDS AND CONCLUSION

While the concept of productivity (the ratio of output to input) is quite simple, the ability to measure and analyze productivity is more difficult. The variety of input has always made productivity measurement challenging. Today, the struggle is made even more difficult by our focus on better management of the output—focusing on meeting customer demand.

It is important for industrial engineers to understand the concept of productivity, why it is important, and what the key elements are that impact productivity. From this the industrial engineer can help his or her organization to better understand and define productivity. A clear definition provides the basis for measurement, analysis, and improvement.

Productivity has always been a relevant issue. The transition to a global economy will make it even more important. The increases in competition will force productivity improvement. Furthermore, as developing countries begin to experience increased standards of living, they will drive even further improvement. This continuous cycle of productivity improvement leading to additional improvement will pick up speed. Industrial engineers have the awesome opportunity and responsibility to lead the effort in managing productivity.

FURTHER READING

Christopher, William F., and Carl G. Thor, eds., *Handbook for Productivity Measurement and Improvement,* Productivity Press, Portland, OR, 1993. (book)

Reich, Robert B., *Productivity and the Economy: A Chartbook,* U.S. Department of Labor, Washington D.C., 1993. (chartbook)

Tiefenthal, Rolf, ed., *H. B. Maynard on Production,* McGraw-Hill, New York, 1975. (book)

Zandin, Kjell B., "Vision and Role of Industrial Engineering in the Environment of Global Business and Economy," presented at the II. National Forum on Productivity, Zlin, Czech Republic, 1997. (presentation)

BIOGRAPHY

Ken Smith is vice president, operations for H. B. Maynard and Company, Inc. He is a 1984 graduate of Grove City College with a bachelor of arts in business administration and computer systems. As a consultant with Maynard, Smith's activities focused on productivity improvement through the application of traditional industrial engineering techniques. He provided consulting services to over 150 companies throughout the United States, Canada, Japan, Sweden, France, and the United Kingdom. In his current capacity, Smith is responsible for all company delivery functions including management consulting, software products, training, and the knowledge center. He actively participates in the Association of Management Consulting Firms (AMCF), the Pittsburgh Technology Council, and the Pittsburgh Chapter of the Institute of Industrial Engineers.

Source: MAYNARD'S INDUSTRIAL ENGINEERING HANDBOOK

CHAPTER 2.2

PRODUCTIVITY IMPROVEMENT THROUGH BUSINESS PROCESS REENGINEERING

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This chapter will discuss the fundamental redesign of an organization and its operations to achieve dramatic performance improvement in the areas of cost, quality, and cycle time. In its broadest application it can impact every aspect of an organization. Industrial engineering skills and techniques that have been used over the years to improve productivity are a major element of the reengineering effort. A BPR project team typically consists of five core skills: project management, human resources, information technology, operational analysis, and cost-benefit analysis. This chapter will focus on how a BPR project is conducted in practice and the important role that the industrial engineer plays in its successful completion.

BACKGROUND

Productivity Remains the Focus

The role of the industrial engineer in most organizations has not really changed over the years. It continues to focus on the design, improvement, and installation of integrated systems of people, materials, information, equipment, and energy. Industrial engineers continue to be at the center of the battle to contain operating costs in the face of relentless pressures to improve performance in areas such as quality and delivery. Since opportunities to increase selling prices are presently almost nonexistent in industries, an organization's very survival often hinges on its ability to manage this productivity challenge. The industrial engineer's contribution is therefore becoming even more critical to the success of an enterprise.

The Rules Are Changing

Although productivity improvement remains an important goal of the industrial engineer, the rules of business are changing and totally new approaches are evolving to achieve that goal.

In recent years we have witnessed changing rules in every area of an organization. Table 2.2.1 outlines the changes occurring in a number of areas as traditional organizations are transformed to reflect the realities of the present and beyond. Changes directly impacting the indus-

TABLE 2.2.1 Organizational Transformation

	Traditional organization		Transformed organization
Structure	Hierarchical	→	Networked
Worker focus	Blue-collar/white-collar	→	Knowledge worker
Scale	Large, stable	→	Flexible
Orientation	Operations	→	Customer
Effort	Individual	→	Team
Key resources	Capital	→	People, information
Rewards	Loyalty and seniority	→	Performance and competence
Economic relationships	Mergers and acquisitions	→	Stategic alliances
Competitive calibration	Multinational	→	Global
Information technology	Support	→	Enabling
Direction	Sound management	→	Leadership

trial engineer include the shifting focus from the blue-collar/white-collar worker to the knowledge worker. Flexibility is being demanded where the customer is the focus and results are delivered through a team effort.

These changes are arising from the new realities, which include:

- Customers demand unique products and faster service.
- Technological innovations happen at a faster rate.
- New products develop more quickly.
- Product life cycles are shorter.
- Governments are forced to reduce deficits.
- Global economy is experiencing low growth.
- No protection exists from global competition.

Derivation of BPR

Authors Michael Hammer and James Champy were the first to use the term reengineering in connection with business processes. In their book, a classic entitled *Reengineering the Corporation* [1], they address what happens when companies seek new ways of getting work done with the goal of producing qualitative change and improvement.

Business process reengineering (BPR) is the fundamental redesign of an organization and its operations to achieve dramatic performance improvements in the areas of cost, quality, and cycle time.

A business process can be described as a group of usually sequential, logically related tasks that provide products and services to both internal and external customers by using organizational resources. It includes two types of processes:

- Operational/core processes carried out by frontline workers in delivering services to customers
- Management support processes that assist the frontline workers in delivering customer services

In reengineering, existing assumptions governing the organization are challenged, paving the way for the radical redesign of how business is conducted. This usually involves the basic reshaping of business processes, organization structure, information technology, and physical infrastructures, and reorientation of corporate values and culture. After reengineering, we have what amounts to a change in corporate culture as illustrated by Table 2.2.2.

TABLE 2.2.2 Corporate Culture Change

	From	To
Work units	Functional departments	Process teams
Jobs	Simple tasks	Multidimensional work
People's roles	Controlled	Empowered
Organization structure	Hierarchical	Flat
Performance measures	Activity	Results
Advancement criteria	Seniority	Performance
Managers	Supervisors	Coaches
Executives	Scorekeepers	Leaders

Where BPR Can Be Applied

BPR can be applied to virtually any organization in both the public and private sectors. Industries that have achieved significant success with BPR include banking and finance, construction, insurance, airlines, and manufacturing.

Benefits from BPR

Benefits are dramatic and can be grouped into four categories: cost, quality, process time, and working environment.

- *Costs can be dramatically reduced.* Costs can be cut by improving the efficiency and effectiveness of performing the tasks involved in a process. Also, cost cutting occurs through the elimination of unnecessary tasks.
- *Quality can be improved.* BPR can reduce error rates in producing and delivering goods and services. It can help you to more closely meet your customers' needs and expectations. Finally, it can result in improved and innovative products and services.
- *Processes are streamlined.* Improvements result in faster access to information, better decision making, and more efficient processes. Idle time between process steps is reduced or eliminated.
- *The work environment is enhanced.* Employee morale climbs as teamwork and commitment are improved and working conditions are enhanced.

BPR PRINCIPLES AND ORGANIZATION

Six Guiding Principles

Successful BPR applications usually follow six guiding principles. These are described as follows:

- *Be customer driven.* The customer is critical to all reengineering steps. Customer needs must drive the overall direction of the business. In deciding on the scope of the project and processes to be targeted, the focus should be on processes that bring high payback to the customer. To this end, serious consideration should be given to customer representation on the design teams. This will ensure that the customers' needs and priorities are fully addressed during the project. The customer continues to be critical at the implementation stage when issues such as disruption of service arise and must be handled. Customer communications are especially important at this stage—asking for feedback will allow you to head off any problems and maximize benefits.

- *Look at "function" first, then "form."* Before deciding on the specific form that the BPR project is to take, it is important to define functionality. That is, starting with the direction of the business, consider why the project is being undertaken. Then, determine what processes are to be redesigned and who within the organization will be involved. Next, decide how these people will participate and address the technologies and policies that will come to bear as the project proceeds. Finally, consider those areas of the physical infrastructure where the project will focus.
- *Position technology as an enabler, not as a solution.* In this age of rapid technological change, it is easy to forget that technology in business is intended to facilitate processes. Therefore, in applying BPR, technology should be used as an enabler and not considered an end in itself.
- *Think cross-functional processes, not individual tasks.* Processes such as product development involve a series of individual tasks that cross a number of functions including marketing and design engineering. A BPR project considers processes rather than the individual tasks that are carried out in these functions, such as prototyping.
- *Set measurable performance targets.* Management usually approves the investment in BPR activity on the basis of specific performance gains that are thought to be achievable. To ensure that BPR is yielding the anticipated result and to provide a basis for project control, specific targets must be set that are measurable. These targets often take the form of a productivity measure such as orders processed per day.
- *Demonstrate success early.* Participants in a BPR project have many competing demands for their time. Also, management has limited resources to invest in the various initiatives that are budgeted for in a company. Therefore, demonstrating success early in a project is critical. This will provide encouragement to the team members who contribute their scarce time and convince management that they should continue to support the project.

Organizing to Reengineer

At KPMG a reengineering project is usually organized around four separate entities. These are the sponsor, the project management team, the design teams, and the steering committee.

- *The sponsor.* This is the individual who is the driving force behind the project. The sponsor can be from any area of the organization and is usually at a fairly senior level in management. This person endorses the project and supports it with the necessary resources throughout its various stages. Resourcing can take the form of financial support and/or people. Besides providing direct support for the project, the sponsor takes every opportunity to informally communicate overall project status and successes within the organization. The sponsor receives recommendations from the project management team and steering committee and provides or obtains the necessary approvals.
- *The project management team.* This is the group that maintains direct control of the project at all stages of development and implementation. It plans every step of the project and leads the work sessions as each step is executed. This team is also responsible for documenting the results of the work at both the interim and final stages. Any presentations on the results of the project are prepared and delivered by the team. Communications in general are handled by the team. It leads all communications initiatives and develops all related material. Finally, the team will directly participate in project implementation. Five core skills are typically represented in the project management team. These skills are project management, human resources, cost-benefit analysis, operations analysis, and information technology. Given this mix of skills, the industrial engineer will naturally have an important role on the team.

PRODUCTIVITY IMPROVEMENT THROUGH BUSINESS PROCESS REENGINEERING

- *Design teams.* These teams, as the name implies, are involved in designing the new way of doing business. Their role is to communicate ideas under consideration to others in the organization so as to obtain their input to the process and to gain ultimate agreement and acceptance. Design teams are made up of functional or program experts, stakeholders, and customers. (Industrial engineers would, of course, be represented in the first group.) Design team members need to be highly energized to ensure progress is steady. They are typically people who are innovative, creative, forward thinking, positive, and solution oriented.
- *Steering committee.* This group is usually made up of representatives of the various functions or departments in an organization, particularly those impacted or potentially impacted by the reengineering project. Its main role is to resolve issues relating to the process and results. It can also present recommendations to the sponsor and communicate progress and findings in conjunction with the project management team. When the reengineering plan has been confirmed, the steering committee will usually continue and lead the implementation phase.

After selecting the members of these four groups, a key step is to clarify their individual roles and how these support the overall role or mission of the entity in which they are members. These become part of the documented terms of reference that guide the reengineering project from start to finish. Misunderstandings by teams as to their operating limits or levels of authority are a common source of problems in BPR projects. A well-defined terms of reference will streamline the decision-making process by ensuring that everyone fully understands the overall goal of the project and what is expected.

EXECUTION—THE NINE DIMENSIONS OF BPR

At KPMG we execute a BPR project by focusing on nine dimensions, as illustrated in Fig. 2.2.1. Each of these dimensions will be described in the following sections.

Business Direction

Since this step will determine the focus for the entire reengineering program, it requires a great deal of emphasis. The critical elements of the business are as follows:

- *Confirming the mandate.* The mandate for a business needs to be reviewed and confirmed. A mandate encompasses the reasons why the company exists, products and/or services offered (now or in the future), and who are its customers. For example, a sample mandate could be for a manufacturer to become a supplier of the full range of instrumentation for customers in the mining industry.
- *Identifying our critical success factors.* Having confirmed the mandate, it is now necessary to determine the success factors that are critical for its fulfillment. These factors can cover a broad range of areas including meeting customers' delivery requirements, satisfying stakeholder needs, and increasing capabilities in certain areas (e.g., upgrading maintenance skill levels). Besides identifying the factors, we must be able to measure our level of success in achieving them. This can take the form of a number of indicators. For example, machine downtime due to maintenance is now 17 percent versus a target of 10 percent.
- *Identifying our reengineering targets.* This can be approached in two ways. One is to assess the gap between the current performance level and the target level, based on the critical success factors discussed previously. From this you decide how much you have to improve and over what period of time. Another approach is to identify, say, the two changes to the way your organization conducts its business that would *dramatically* improve its performance. Then,

PRODUCTIVITY IMPROVEMENT THROUGH BUSINESS PROCESS REENGINEERING

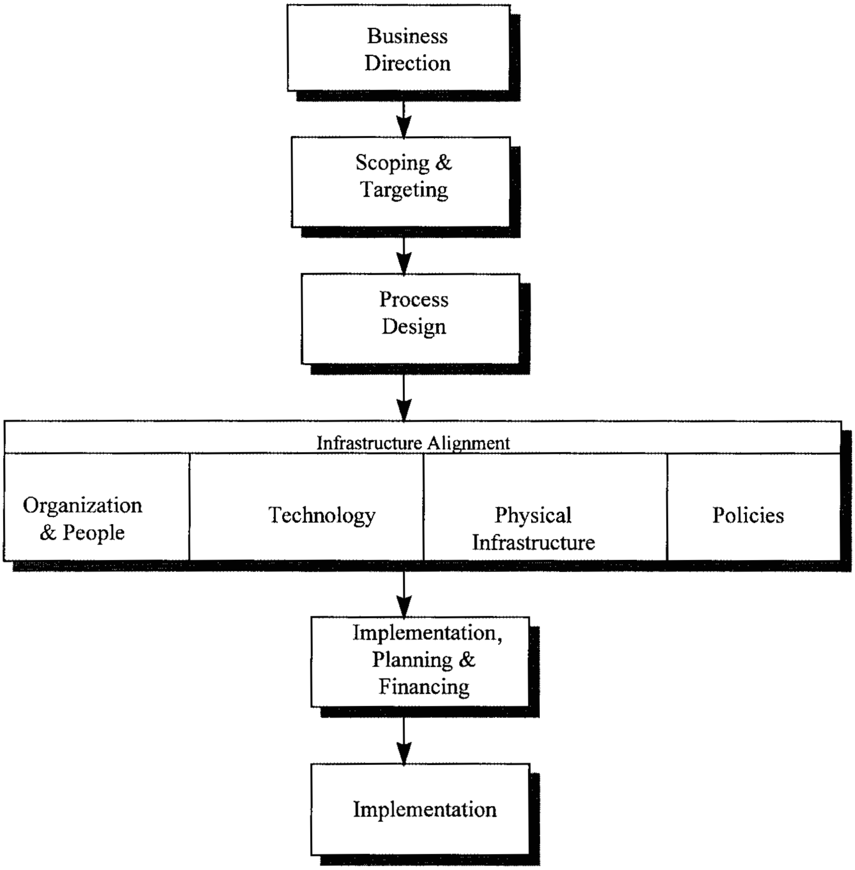
Business Direction
Scoping & Targeting
Process Design
Infrastructure Alignment
Organization & People
Technology
Physical Infrastructure
Policies
Implementation, Planning & Financing
Implementation

FIGURE 2.2.1 The nine dimensions of BPR.

determine the measurable results that could be expected if these changes were to be implemented. Table 2.2.3 is an example of some customer-focused reengineering targets.

- *Confirming our shared values and principles.* A final aspect of business direction relates to the values and principles shared by employees and the company's trading partners. One approach is to decide the terms you would like these people to use when describing

TABLE 2.2.3 Customer-focused Reengineering Targets

Customer stakeholder requirements	Performance indicators	Reengineering targets
Quick and on-time service	Cycle time per transaction	Reduce service delivery cycle time by 30%
Accuracy	Number of errors	Reduce number of errors to 0%
Cost	Cost of service	Reduce cost by 40%

PRODUCTIVITY IMPROVEMENT THROUGH BUSINESS PROCESS REENGINEERING

your organization. For example, "committed to people development" could be one way to express such values or principles. Another approach is to identify the shared values and principles that should guide the future provision of your products or services and the reengineering of your business processes.

Scoping and Targeting

When the business direction has been confirmed, it is possible to begin the step of reviewing existing business processes and selecting those to be redesigned. Figure 2.2.2 illustrates the activities that are carried out in scoping the processes and targeting the opportunities to be pursued. These activities are described in the following sections.

Information Gathering and Data Collection (Multiple Lines of Evidence). This is accomplished in three ways: as-is process modeling, interviews with appropriate personnel, and research (e.g., literature review, expert advice).

- *As-is process modeling.* Flow diagrams are used to model processes as illustrated in Fig. 2.2.3. The symbols used in the diagram are explained in the example in Fig. 2.2.4.
  A process flow diagram has four elements:

1. Activities that must be performed to produce the required output(s)
2. The information required by each subprocess
3. The external entities or stakeholders who are involved in the process in some way
4. Performance estimates

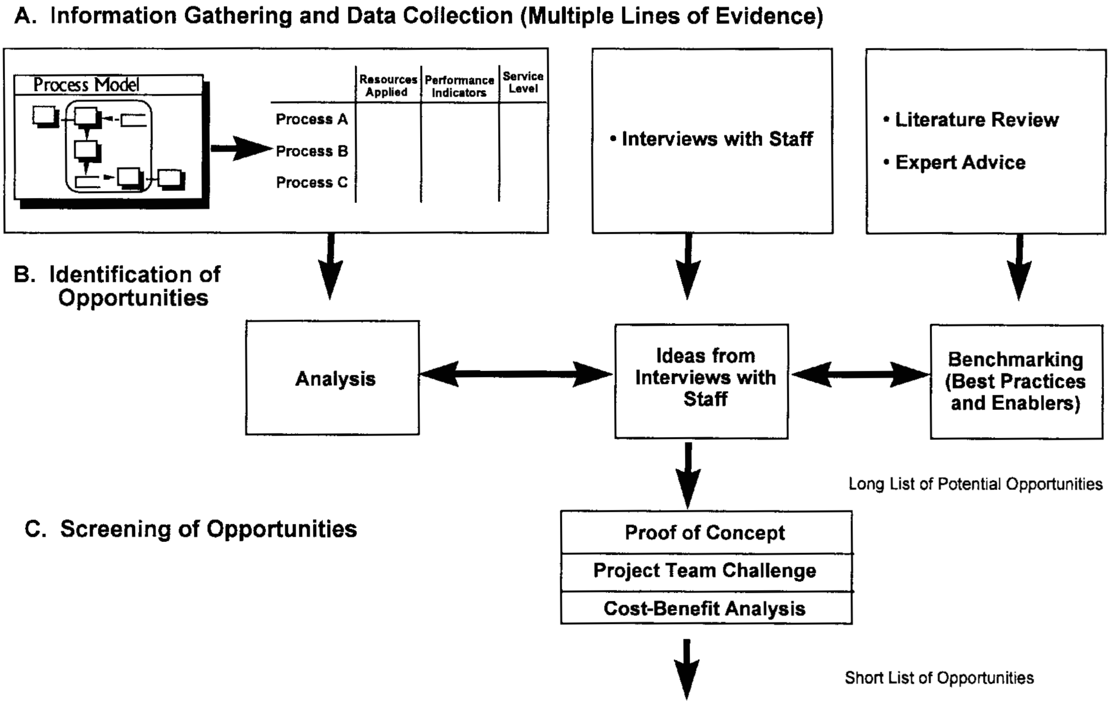
A. Information Gathering and Data Collection (Multiple Lines of Evidence)
Process Model
Resources Applied
Performance Indicators
Service Level
Process A
Process B
Process C
• Interviews with Staff
• Literature Review
• Expert Advice
B. Identification of Opportunities
Analysis
Ideas from Interviews with Staff
Benchmarking (Best Practices and Enablers)
Long List of Potential Opportunities
C. Screening of Opportunities
Proof of Concept
Project Team Challenge
Cost-Benefit Analysis
Short List of Opportunities

FIGURE 2.2.2 Scoping and targeting activities.

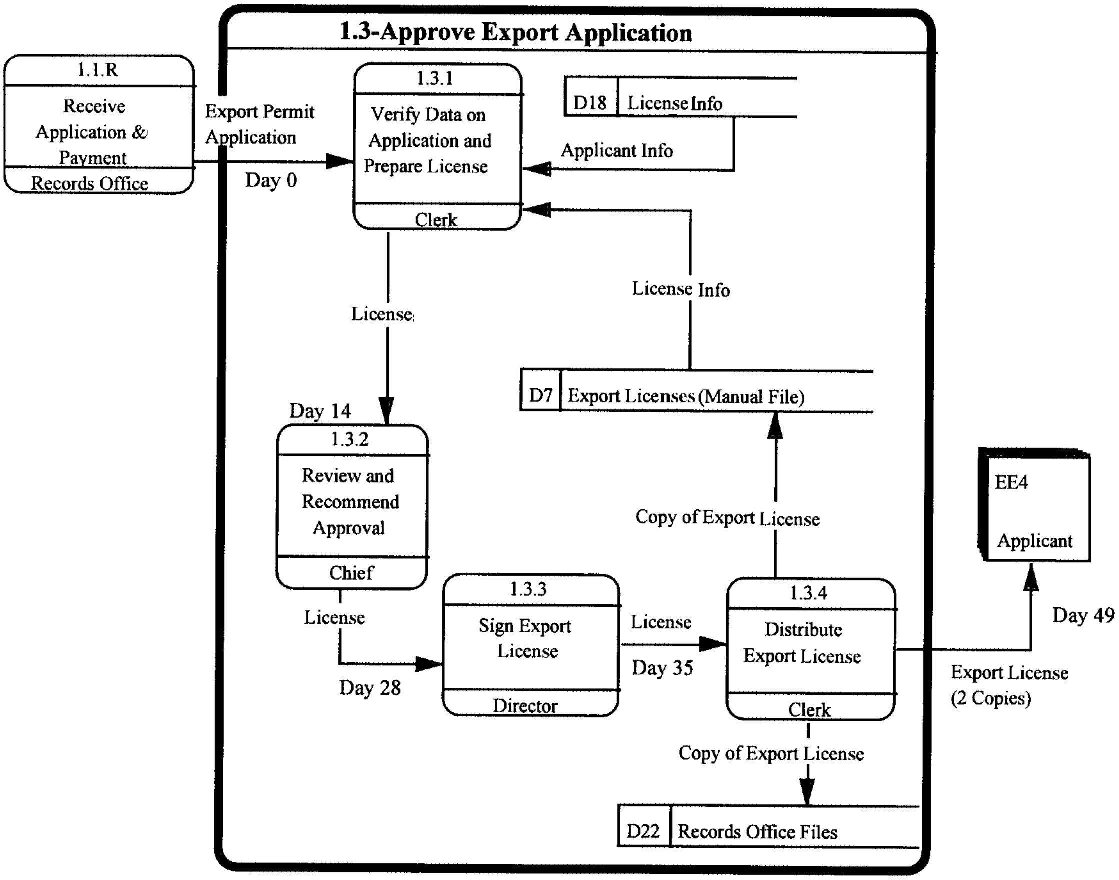
1.3-Approve Export Application
1.1.R
Receive Application & Payment
Records Office
Export Permit Application
Day 0
1.3.1
Verify Data on Application and Prepare License
Clerk
D18
License Info
Applicant Info
License Info
License
D7
Export Licenses (Manual File)
Day 14
1.3.2
Review and Recommend Approval
Chief
EE4
Applicant
Copy of Export License
License
Day 28
1.3.3
Sign Export License
Director
License
Day 35
1.3.4
Distribute Export License
Clerk
Day 49
Export License (2 Copies)
Copy of Export License
D22
Records Office Files

FIGURE 2.2.3 Example of flow diagram.

- *Interviews.* Identify the people directly and indirectly involved in the process and solicit their ideas on any opportunities for improvement.
- *Research.* A third line of evidence gathering is through research on one or more aspects (e.g., alternative ways of producing a component of a product to achieve a higher quality or lower cost). Sources can include trade journals, experts in the particular area, and the Internet.

Identification of Opportunities. With the information and data assembled in the previous step, it is now possible to identify a list of potential opportunities for improvement. The approach to doing this is described in the following section.

- *Analysis based on the process models.* Critical business processes can be reviewed through as-is mapping to achieve the following:
  1. Identification of bottlenecks, redundancies, and inefficiencies. The symptoms are:

     Exorbitant costs

     Multiple or unnecessary levels of approval

     Revisions of the work of someone else

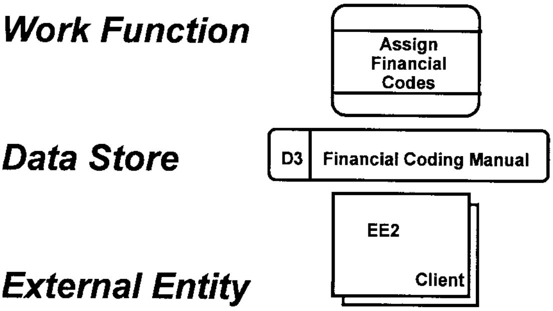

FIGURE 2.2.4 Symbols used in a flow diagram.

Reliance on the knowledge or approval of one specific individual (i.e., no back up)
High error rates (e.g., redoing work)
Decisions made at inappropriate levels of management
Activities that involve clarifications, transportation, storage, set-up time, repairs

2. Assessment of current performance and refining performance targets. This is a critical component of the review of existing processes. The steps involved are:

   Identifying key performance indicators
   Assessing current performance level
   Assessing target performance
   Identifying performance gaps and translating these into reengineering targets

3. Identification of potential enablers. An example:

Need	*Possible IT Solution*
Reduce storage costs	Imaging
Allow user wider access to information	Expert systems, networks
Speed access time	Touch screens
Provide fast data entry	Bar codes, pen-based computing
Improve item tracking	Bar codes
Standardize information	Electronic commerce—EDI
Increase flexibility	Client/server infrastructure
Increase system's user-friendliness	Graphical user interface
Speed transaction flow	Kiosks, interactive voice response, fax back
Reduce defect rate	Bar codes, expert systems

4. Identification of quick hits. Although these may be of relatively low value, it is important that the reengineering effort demonstrate early successes so that confidence is gained and long-term support for the work is established.
5. Identification of constraints. During the analysis work, it will often become apparent that certain short- or long-term constraints exist with respect to improvement opportunities (e.g., a licensing agreement that prevents the use of alternative manufacturing approaches).
6. Determination of order of magnitude cost-benefits for opportunities identified. These will be detailed enough to allow decisions as to whether to pursue the ideas and to set priorities for future development.

- *Benchmarking.* This has become a popular approach for determining best practices and enablers and hence for identifying opportunities for improvement. It consists of four steps:
  1. Identify comparators by selecting leaders/innovators.
  2. Gather information on performance.
  3. Compare practices, policies, and use of technology enablers.
  4. Document, analyze performance gaps, and identify opportunities for improvement.
- *Ideas from interviews with staff.* These ideas are summarized and compared or assimilated with the ideas arising from the analysis work. In this way, confirmation is obtained as to the validity of the ideas or opportunities. Also, the best practices and enablers arising from the benchmarking exercise represent a third stream of information against which staff ideas can be compared and validated.
- *Screening of opportunities.* The objective at this stage is to develop a short list from the long list of opportunities prepared previously. Using the information on hand from the identification stage, the long list is screened with respect to three tests, which are:
  1. Proof of concept—the criterion here is how the concept being proposed will actually deliver the required results and with what degree of certainty.
  2. Project team challenge—here, the project team is asked to examine the long list of oppor tunities and rank them according to agreed criteria such as early results, broad support from the organization in general, and satisfying the business direction of the company.
  3. Cost-benefit analysis—this is carried out to the level of detail needed to identify the superior projects or opportunities from those selected by the project team.

Figure 2.2.5 illustrates how the previously described steps would be used to identify reengineering opportunities.

Process Design

The key to achieving breakthroughs in productivity is to start with a clean slate. Trying to build on existing process designs tends to limit creativity and will usually not yield the dra-

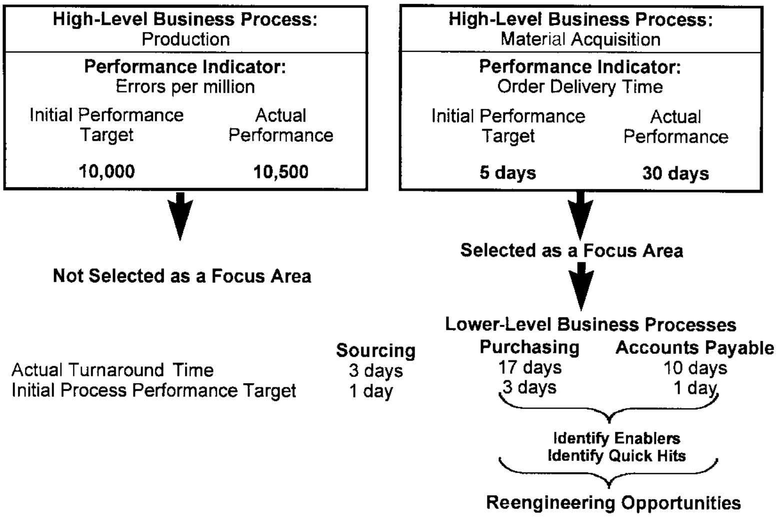
High-Level Business Process:
Production
Performance Indicator:
Errors per million
Initial Performance Target
Actual Performance
10,000
10,500
Not Selected as a Focus Area
High-Level Business Process:
Material Acquisition
Performance Indicator:
Order Delivery Time
Initial Performance Target
Actual Performance
5 days
30 days
Selected as a Focus Area
Lower-Level Business Processes
Sourcing
Purchasing
Accounts Payable
Actual Turnaround Time
Initial Process Performance Target
3 days
1 day
17 days
3 days
10 days
1 day
Identify Enablers
Identify Quick Hits
Reengineering Opportunities

FIGURE 2.2.5 Selection of reengineering opportunities.

matic improvement that management is seeking through BPR. By starting fresh, process design can reflect the full creative forces of the design team and often leads to entirely new and better ways of achieving the desired result.

Six guiding principles help to ensure that process design is focused and will yield the desired results. These are

- *Identify what, not who or where.* The primary design issue is what is to be accomplished, not who will perform the activities or where they will be carried out. The latter items need to be addressed eventually, for example, to determine costs and benefits by opportunity.
- *Design processes for the vast majority of situations, then look after the exceptions.* Attempting to design a process from the start that will satisfy all possibilities tends to weaken the impact of the new approach and not result in the desired breakthrough.
- *Minimize permanent control functions.* Phasing in a new process design often requires temporary control functions (e.g., quality checks) to be in place until the process is running smoothly. However, such functions should be eliminated whenever possible as the new design matures.
- *Confirm that each function adds value to the delivery of products or services.* Functions that do not add value, such as material handling and inspection, should be avoided in the new design.
- *Screen all functions for consequences of elimination.* A simple test for the need to include a function in a process sequence is to ask the question, "What would happen if the function was not performed at all?" In some cases, the consequences are insignificant and the function can be eliminated with minor adjustments to other responsibility assignments.
- *Confirm consistency with the business direction.* All new process designs must be aligned with the direction established for the organization. For example, if the direction is toward excellence in product or service quality, then the process must be designed so as to not compromise quality improvement efforts.

The clean-slate approach to process design is often challenged during the design stage by real and/or artificial constraints. Real or valid constraints pertain to items such as government regulations (e.g., safety) and company policies or values. Artificial constraints that should be ignored include standard procedures that at one time represented best practices but no longer do, and historical habits represented by the statement "We've always done it this way."

Infrastructure Alignment

Business processes form the linkage between the components of an organization. These components represent the various resources that make up the business infrastructure. They include organization and people, technology, physical infrastructure, and policies. After business processes have been redesigned, consideration must be given to how the available resources will support the new processes.

This reallocation of resources is a critical step in BPR. It represents an opportunity to not only introduce new and innovative business processes, but also to position them so as to ensure that the components of the organization are linked and aligned to support overall business strategy. This infrastructure alignment, as illustrated in Fig. 2.2.6, transforms the scattered resources of today's business into a cohesive structure linked by redesigned business processes that are geared to meeting tomorrow's demands.

Four dimensions support this infrastructure realignment: organization and people, technology, physical infrastructure, and policies. These are described in the following sections.

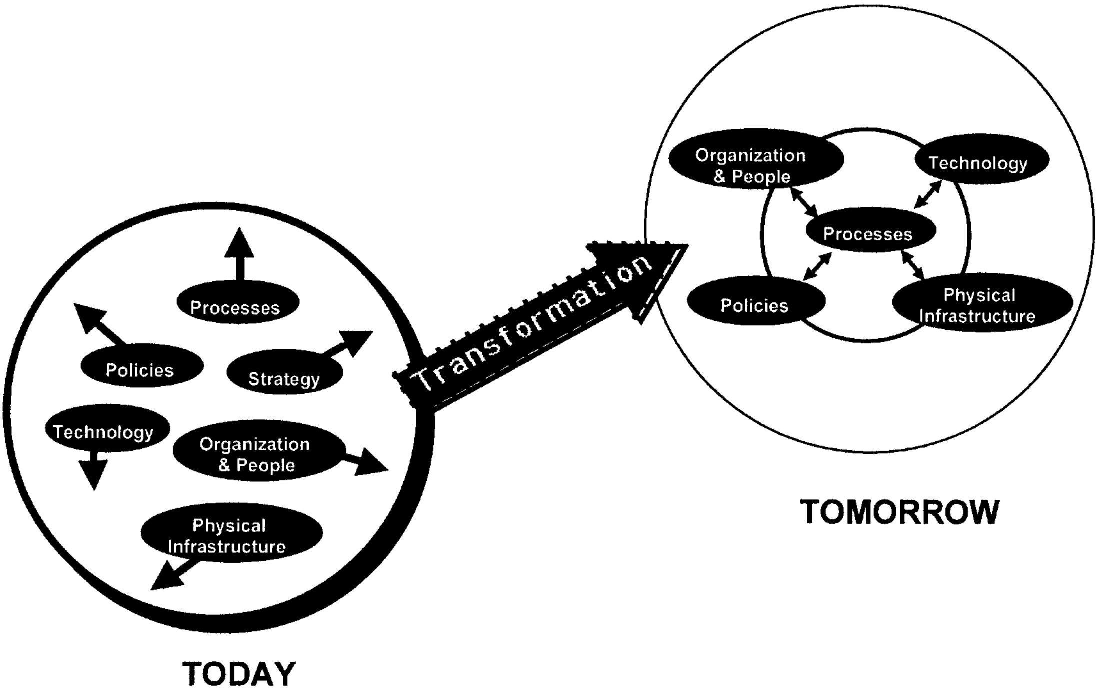

FIGURE 2.2.6 Infrastructure realignment.

Organization and People. This dimension will have a number of outputs, including:

- *Estimate of required number of employees and cost of human resource requirements.* A human resource planning model is used to estimate staff requirements. Table 2.2.4 illustrates how a model is used to estimate the number of people needed to conduct a reengineered process. Workload volumes are estimated using a number of sources including historical trends, staff estimates, customer forecasts, and workload drivers (e.g., sales revenue). The work effort or time per unit can be obtained from staff estimates, external benchmarks, sample testing, or established time standards.
- *Graphic representation of proposed organizational model.* This model should organize people around the processes (i.e., process owners, process teams) rather than functions. In general, the organization structure should be as flat as possible with respect to management levels and spans of control. Finally, consider opportunities for multiskilling and avoid the inflexibility associated with specialization.
- *Profiles of key positions in each organizational unit.* This is a position outline indicating title, scope of responsibility, and reporting relationships.
- *Implementation work packages.* These documents outline the work plan needed to implement the organization and people dimension of the reengineering project.

Technology. The outputs of this dimension will include:

- *Target technology environment.* This is a definition of the technology area(s) to be pursued in support of the reengineered processes. Proposed new processes and technology enablers may not necessarily require major changes to the existing technology base.

TABLE 2.2.4 Estimating Number of Employees Required—Example

Redesigned process	Workload (volume	×	Work effort (time)	=	Total level of effort (time)	=	Total FTEs (at 190 productive days*)
	1,000 licenses	×	2.5 working days	=	2,500 working days	=	13 full-time equivalents
				*	total work days		260
					sick leave		(5)
					vacation		(15)
					statutory holidays		(10)
					net available days		230
					training		(5)
					administration at 10%		(23)
					indirect time at 5%		(12)
					net productive days		190

- *Impact assessment of new technology.* This provides input to the overall cost-benefit analysis for the reengineering initiative. For example, new technology could result in a significant impact on the workforce with respect to skill level requirements and hence retraining needs.
- *Implementation of work packages.* These documents outline the work plan needed to introduce the planned technology.

Figure 2.2.7 illustrates how technology relates to the other dimensions with respect to inputs and outputs.

Physical Infrastructure. This includes the following outputs:

- *Target physical infrastructure environment.* This describes items such as tools, equipment, and space that have been identified as necessary to the completion of the reengineering plan.

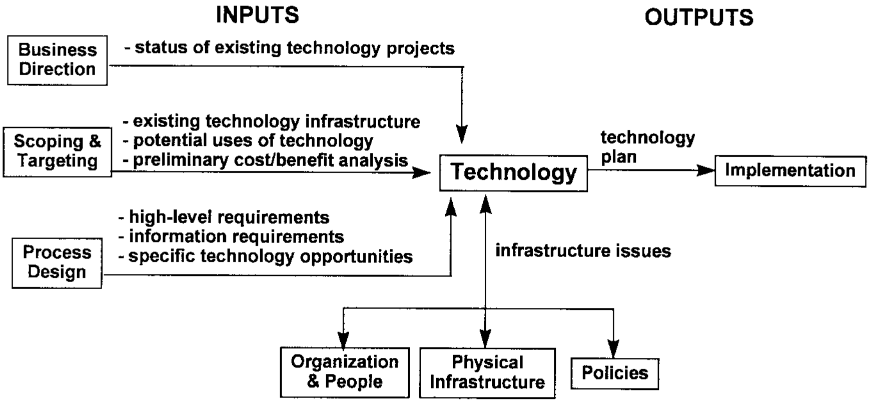
INPUTS
OUTPUTS
Business Direction
- status of existing technology projects
Scoping & Targeting
- existing technology infrastructure
- potential uses of technology
- preliminary cost/benefit analysis
Technology
technology plan
Implementation
Process Design
- high-level requirements
- information requirements
- specific technology opportunities
infrastructure issues
Organization & People
Physical Infrastructure
Policies

FIGURE 2.2.7 Relationship of technology to other dimensions.

- *Impact assessment.* This identifies how targeted changes to the physical infrastructure will impact areas such as the working environment. For example, new workstation layouts may mean better ergonomics for the workers or less walking.
- *Implementation of work packages.* These documents outline the work plan needed to implement the physical infrastructure dimension of the reengineering project.

Policy, Regulation, and Legislation.

- *Target description of policies, regulations, and legislation.* This describes developments with respect to the areas necessary for the successful completion of the reengineering project. For example, company policies may have to change employee cross-training for a new process design to be effective.
- *Impact assessment.* This describes how new policies, regulations, and legislation will impact reengineered operations. Such changes could impact anything from facilities layout to reporting frequencies to worker health and safety.
- *Implementation work packages.* These documents outline the work plan needed to implement the policy, regulation, and legislation dimension of the reengineering project.

Implementation Planning and Financing

The outputs from this dimension will include

- *Detailed implementation work packages.* These are a compilation of the individual work packages developed under the infrastructure alignment dimension.
- *Bundling of work packages into transition phases.* Individual work packages are combined to form an overall phased transition plan for moving from existing processes to reengineered processes.
- *Final cost estimates for reengineering initiatives.* At this point, all of the cost estimates associated with the project are assembled, including implementation and any financing costs.
- *Schedule for each phase.* A detailed schedule is produced, by phase, indicating the target completion dates by activity and who is responsible for each activity.
- *Financing options for the transition period.* Any funding required during implementation—to cover either operating or capital costs—should be identified. Sources of financing, including options, should also be determined by phase to cover funding needs during the transition period.

Implementation

This dimension typically refers to full implementation of BPR involving a number of projects. Prior to this there will have been preliminary implementation stages. These include the quick hits that occur during the scoping and targeting dimension and the pilot projects that are established following process design. Figure 2.2.8 illustrates the relationship between the dimensions in a BPR project and how the three stages of implementation occur throughout the flow.

Two other aspects of BPR are indicated in Fig. 2.2.8. Process measurement occurs throughout the reengineering project to assess the level of success being achieved. Measurement is usually made in units (e.g., person-hours, elapsed hours, dollars) that reflect the efficiency with which a process is carried out. A second aspect of a BPR project that occurs as the project progresses is change management, which is described in the next section.

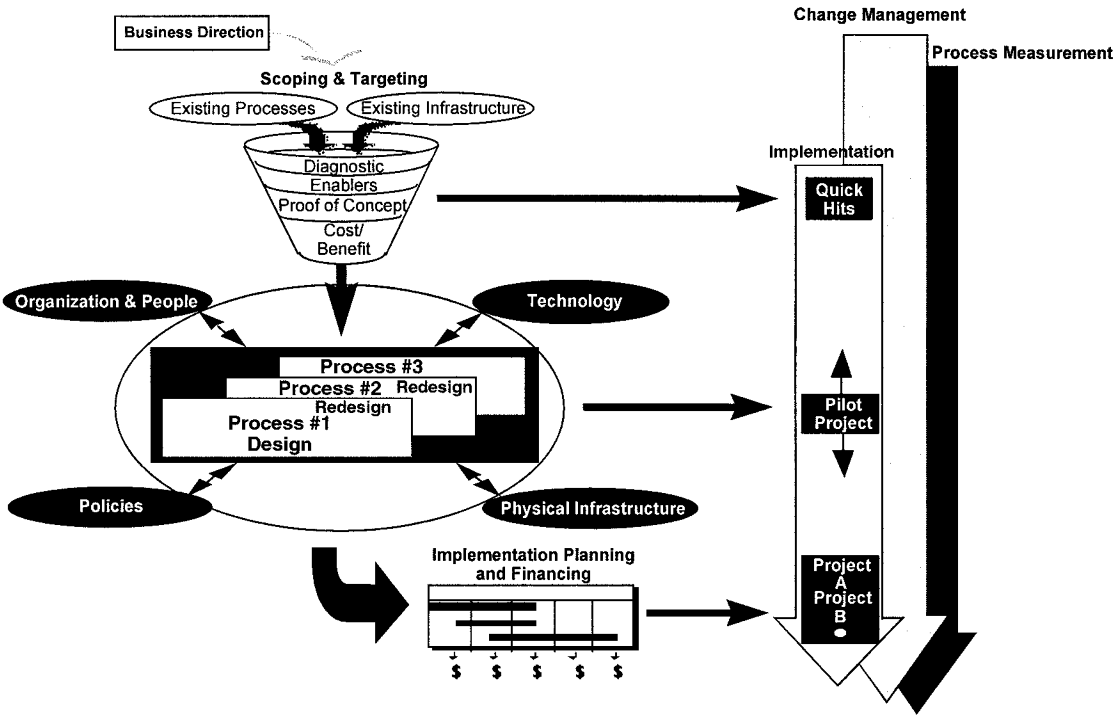
Business Direction
Scoping & Targeting
Existing Processes
Existing Infrastructure
Diagnostic
Enablers
Proof of Concept
Cost/
Benefit
Organization & People
Technology
Process #3
Process #2 Redesign
Redesign
Process #1
Design
Policies
Physical Infrastructure
Implementation Planning and Financing
$ $ $ $ $
Change Management
Process Measurement
Implementation
Quick Hits
Pilot Project
Project A
Project B

FIGURE 2.2.8 BPR flows.

CHANGE MANAGEMENT

Having a well-planned BPR project does not necessarily guarantee success. Managing organizational change is the key challenge in any project of this type. A project can succeed or fail depending on how well change management is carried out.

Change management should begin at the start of the project and then carry through into each phase of the exercise.

At the Start of the Project

Begin by evaluating the degree to which the organization is ready for change. Ask the following questions:

- Are those affected aware that changes are coming?
- To what degree have past change initiatives been successful?

Then, identify and mobilize change agents within the organization. The change agents identified and the manner in which they are mobilized will depend on the answers received to the previous questions. A change agent is not necessarily a person at a high level in the organization. It is someone who is familiar with any traditional resistance to change that has existed in the past and has the ability to muster the necessary forces that will overcome the resistance.

Throughout the Project

As the project proceeds, it is critical that any sources of resistance to change be detected and appropriately addressed. This can be done in several ways.

1. Generate a sense of urgency that will challenge the status quo.
2. Communicate constantly.
   - Repeat messages often.
   - Change the vehicles and the words.
   - Focus the message toward achieving the change, not looking at the past.
   - Provide as much information as possible.
   - Communicate progress.
   - Acknowledge the costs.
   - Acknowledge the successes—producing on-time results.
3. Ensure that senior management leads by example.
4. Provide any necessary training.
5. Reward people's efforts.

The risk of failure can be minimized through careful planning and preparation. Do not hesitate to draw on the necessary resources and authority to overcome obstacles or resistance to change.

Continuous Improvement

Given the emphasis that many organizations place on continuous improvement, change management must become an integral part of the organizational culture. This will help to ensure that performance improvements resulting from BPR initiatives are sustained over time and ultimately lead to opportunities for additional gains.

FUTURE TRENDS—BUSINESS PERFORMANCE IMPROVEMENT

Most organizations, particularly those with continuous improvement programs, have experienced a proliferation of change projects—large and small—that are concurrently underway. In some cases, these projects may be uncoordinated, stand-alone initiatives that frequently overlap (or even contradict) one another.

In order to align disparate and uncoordinated change efforts, a shared understanding or framework of the dynamics of the change process is necessary. Many organizations are recognizing this need and are coordinating all of their change efforts within a broad business transformation framework. The principles of BPR will continue to be applied in improvement projects conducted within this new framework.

The framework that is evolving provides a flexible, participative approach for transforming businesses in a manner that leads to tangible results—revenue growth, enhanced customer service, improved quality, or dramatic time-cost reductions.

Therefore, we are seeing a trend to conducting BPR projects within a framework that coordinates all improvement and change initiatives. This trend recognizes that the overall goal is performance improvement for the entire organization. KPMG refers to this business transformation process as business performance improvement (BPI) [2].

PRODUCTIVITY IMPROVEMENT THROUGH BUSINESS PROCESS REENGINEERING

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2. KPMG, "Business Performance Improvement," Waterloo, Ontario, 1997. (report)

BIOGRAPHY

Brian Bush, P.Eng., is a management consultant with KPMG based in Waterloo, Ontario, Canada. His consulting career spans a period of 18 years, and he presently directs KPMG's industrial engineering practice. Prior to consulting, he held positions in industry as an industrial engineer and plant manager. He holds a B.A.Sc. (mechanical engineering) and an M.B.A. from the University of Toronto. He is a certified management consultant (CMC) and a senior member of the Institute of Industrial Engineers (IIE). He is currently a member of the board of directors and is past president of the Toronto chapter of the IIE.

Source: MAYNARD'S INDUSTRIAL ENGINEERING HANDBOOK

CHAPTER 2.3

TOTAL PRODUCTIVITY MANAGEMENT

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Total productivity management, or TP management as it is generally known, provides a system for coordinating all the various improvement activities occurring in a company so that they contribute to top management's goals for the entire company. Starting with a corporate vision and broad goals, these activities are developed into supporting objectives, or targets, throughout the organization. The targets are specifically and quantitatively defined and a contribution factor is assigned to each, reflecting the degree to which it furthers high level goals. This chapter describes how to introduce, develop, and expand a TP management program and explains the importance of factors such as top management sponsorship, breaking down conventional territorialism, and sharing the "big picture" with all participants.

Companies implement TP management for a variety of reasons, which can be used to define types of TP management programs. Two actual case studies are introduced, reflecting quite different types of TP programs and the quantitative and qualitative results are explained.

INTRODUCTION

The objective of total productivity (TP) management is to coordinate all productivity improvement activities within an organization and create a system that responds with flexibility to the intense changes typical of today's business environment. TP management facilitates extension of the management/control function across a complex organization and stimulates improvement activities at all levels to achieve corporate goals.

TP management begins with an image of "how the business should be" or "how we want it to be," in terms of management objectives. TP management then creates a system for binding all the elements that make up the organization into an organic team and managing its continuous improvement by setting specific achievement goals and promoting their accomplishment.

TP management provides a means for translating the goals of top management into clear achievement targets (overall targets) and then developing each overall target into one or more concrete individual targets for subgroups of the organization. Action plans are then developed by each group to accomplish its goals. Naturally, at each stage of the business process (for example, planning, design, scheduling, implementing, and management), planned activities are evaluated and those expected to be the most effective (in terms of expected benefits versus required resources) are selected.

Finally, to ensure that the chosen plans and activities achieve the intended results and contribute to the organization's management objectives, a system is created to coordinate the whole program effectively.

TP management is, in a sense, a top-down program because it always starts by identifying the goals of top management. Then, it employs the following concepts:

- Break away from conventional internally oriented, comparative productivity campaigns that seek incremental improvements, and instead focus on achieving ambitious new targets.
- Change from *kaizen* activities, which build up incremental improvements, to an approach based on an image of the ideal—seek extreme results.
- Pursue the concept of the ideal total system.
- Apply management technology in a systematic and theoretically correct manner.
- Evaluate the current condition of management and further develop the company's own management techniques.

TP management also requires that each company develop and establish its own original management system. The concepts underlying TP management offer a new way of thinking about productivity.

ADOPTION OF TP MANAGEMENT AND TECHNIQUES FOR TP EXPANSION

Focusing on Objectives to Build a Leading Company

For 10 years our organization has offered management guidance on TP management, from its introduction and expansion throughout an organization to the confirming of actual achievements. During that time, we have provided such management guidance to over 70 companies or other business units in a variety of industries. In factory situations, the work focused on improving performance in the areas of quality (Q), cost (C), and delivery (D).

Originally these activities were performed to increase company profit, and they were guided solely from the company side. During the last 4 or 5 years, however, there has been a shift to activities that focus on customer satisfaction (CS). In addition, there has been an increase in activities addressing ES (employee satisfaction) or SS (social satisfaction, including environmental issues). This reflects a greater sense of social responsibility on the part of companies, and today TP management programs are conducted with a recognition of the need to reform the enterprise itself.

Structure and Systems for Implementing TP Management

The foundation of every TP management program must be a clear understanding of management's goals as to the kind of results desired through productivity improvement. These goals should be expressed in terms of achieving the ideal result—creating the kind of business unit management is striving for. Before a TP management program is started, it is essential for top management to identify the most important management themes or topics facing the company (or other business unit), based on its current situation and including its competitive position in the market.

Identifying management themes in this way gives the whole organization a direction for overall productivity improvement. Then, to achieve improvement, it is necessary to describe concretely exactly what results are expected and set these as achievement targets.

Management themes, meaning subjects that management wants the company to address, are generally of two types. One type of theme focuses on numerical measures of production activity and defines targets by the business results that are desired from the improvement activity. Such themes are called *results-focused* management themes. For example, seeking a drastic improvement in market share percentage by strengthening a product's competitive power would be a results-focused theme.

The other type of theme focuses on the production system itself and considers how innovative improvements can be made and how the system can be strengthened. Management themes of this type are called *structural-innovation* themes. A theme like becoming the best (industry type) factory in the world would be an example of a structural-innovation theme, because it would envision extensive innovation to achieve extreme improvements in productivity. See Fig. 2.3.1 for an outline of a TP management program.

The Basic Flows of TP Management

Basic Flows of TP Activity. TP management is composed of two basic flows. One is an externally oriented flow that aims at achieving top-notch customer satisfaction through best of class quality, cost, and delivery (Q, C, and D). The other is an internally oriented flow that seeks to make improvements in the structure and core capability of the company or other business unit. Internally oriented targets are often expressed as an "image of the ideal we want to achieve" (e.g., to evolve into a world-class factory) and generally require making major renovations in the business unit.

Another aspect of TP management is to ensure that both management's externally oriented targets (for example, targets for improved customer satisfaction) and internally oriented targets are pursued in parallel so that they can be achieved simultaneously.

Targets, whether externally or internally oriented, must further a company's overall objectives, such as improving competitive strength through Q, C, and D to better satisfy customers. In all TP management programs, participants must recognize that the objective is not for individual business units to compete with one another, but for the competitive strength of the whole company to be improved.

Figure 2.3.2 shows an outline of the structure of the TP program at Company A, which is introducing TP management at the present time. Through such activity, TP management programs seek to achieve the following goals:

1. Clarify the objectives that the company (or business unit) as a whole should pursue, focus and coordinate the efforts of all parts of the company, and work simultaneously toward accomplishment of the objectives.
2. Create an organization that can take the general, companywide objectives and systematically develop them into specific targets, based on confirmation of which activities are most important for accomplishing corporate goals.
3. Create and standardize a three-level process, in which (1) general objectives are developed into (2) individual targets, which are then translated into (3) plans and activities. This process ensures that each plan and activity advances individual objectives and targets that are in accordance with management goals.
4. Take advantage of the strengths and capabilities of all employees in the organization and challenge them to grow. Then, make it clear to them how their actions are contributing to

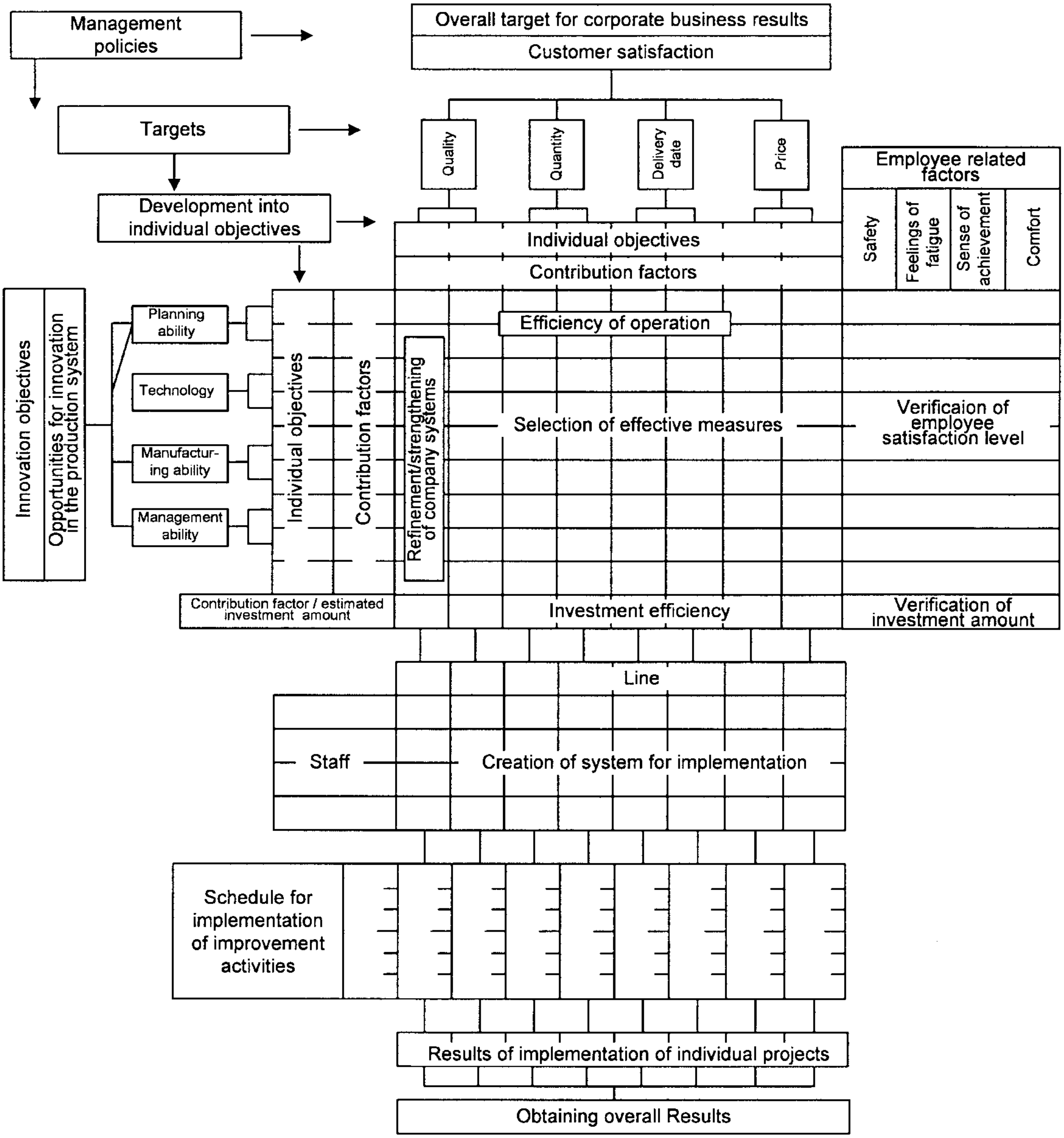

Management policies
Overall target for corporate business results
Customer satisfaction
Targets
Quality
Quantity
Delivery date
Price
Employee related factors
Development into individual objectives
Safety
Feelings of fatigue
Sense of achievement
Comfort
Individual objectives
Contribution factors
Innovation objectives
Opportunities for innovation in the production system
Planning ability
Technology
Manufacturing ability
Management ability
Individual objectives
Contribution factors
Refinement/strengthening of company systems
Efficiency of operation
Selection of effective measures
Verificaion of employee satisfaction level
Contribution factor / estimated investment amount
Investment efficiency
Verification of investment amount
Line
Staff
Creation of system for implementation
Schedule for implementation of improvement activities
Results of implementation of individual projects
Obtaining overall Results

FIGURE 2.3.1 Overall system for applying TP management.

the targets and objectives. This will increase their eagerness to participate in improvement activities.

5. Create a strategic management system that can adapt to changes in the business environment and at the same time obtain dramatic improvements in business results based on management's design.

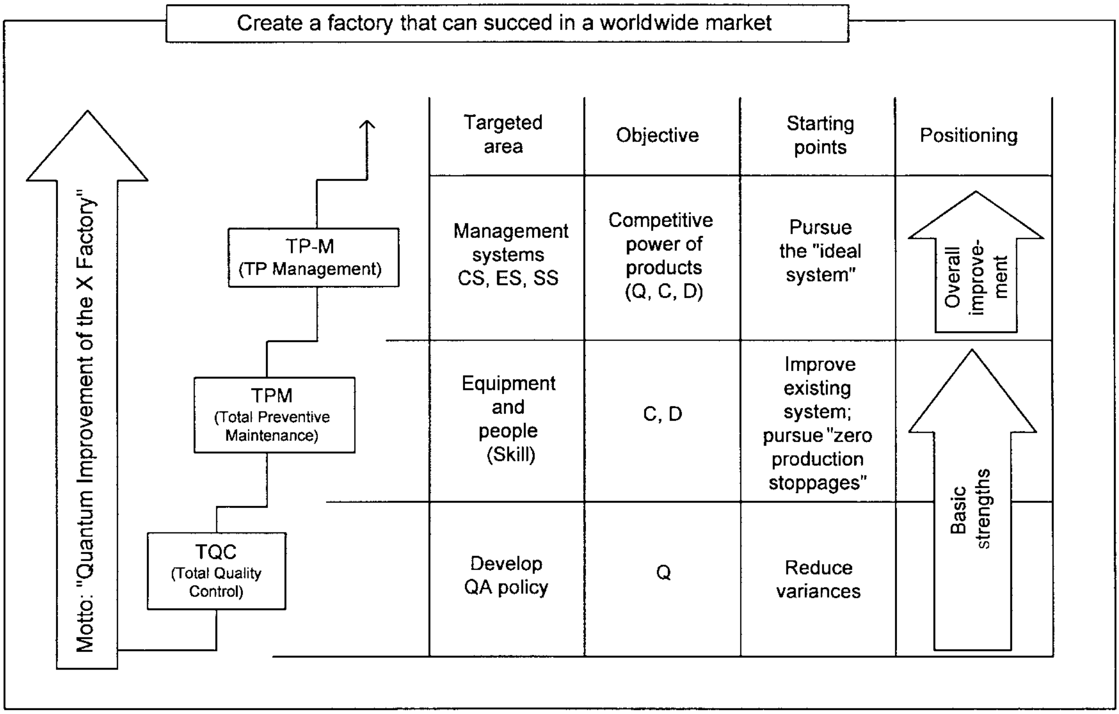

Create a factory that can succed in a worldwide market
Motto: "Quantum Improvement of the X Factory"
TP-M
(TP Management)
TPM
(Total Preventive Maintenance)
TQC
(Total Quality Control)
Targeted area
Objective
Starting points
Positioning
Management systems CS, ES, SS
Competitive power of products (Q, C, D)
Pursue the "ideal system"
Overall improve-ment
Equipment and people (Skill)
C, D
Improve existing system; pursue "zero production stoppages"
Basic strengths
Develop QA policy
Q
Reduce variances

FIGURE 2.3.2 Positioning and general concept of Company A's TP program.

The basic approach of TP management is continuous development or rollout of the program, while pursuing the previous five disciplines. Viewed as a process, the flow would be: (1) set strategic management goals, (2) develop them into specific targets for each area within the organization, (3) select the most effective plans and activities, (4) establish an active organization for managing the program, and (5) achieve a high level of business performance results. The overall structure for this kind of TP activity is shown in Fig. 2.3.3.

Stage 1: Establishing Strategic Overall Goals. TP management puts great emphasis on the overall goals of top management. Strategic overall goals are established to enable the company to (1) accomplish its mission of growth and profitability, and at the same time (2) remain sensitive to changes in the internal and external business situation (based on a customer-oriented mind) and (3) respond promptly to such changes.

To establish overall goals, the first steps are to:

1. Correctly assess changes in the company's external situation (trends in customer needs, relationship to the global environment, and relationship to developments in foreign markets).
2. Establish the right conditions inside the company, the proper management vision, and any necessary strategic management policies. At the same time, thoroughly analyze the competitive situation and determine the level of Q, C, and D required to achieve product distinction in the market.
3. Using the results of steps 1 and 2, establish the objectives of mid- and long-term management plans, examine TP management from the broad perspective, and then set specific objectives, step by step.

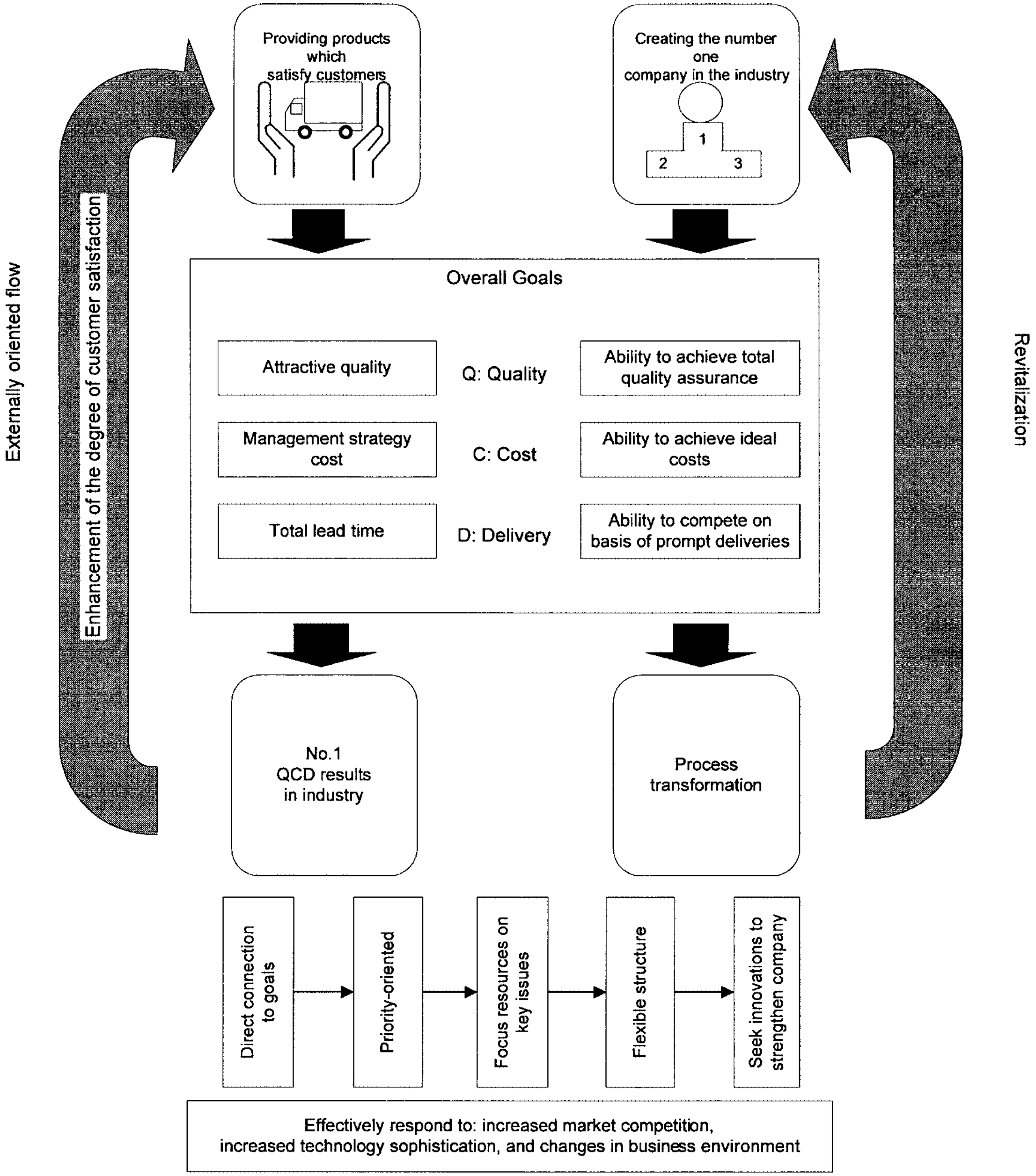

Providing products which satisfy customers
Creating the number one company in the industry
1
2
3
Overall Goals
Attractive quality
Q: Quality
Ability to achieve total quality assurance
Management strategy cost
C: Cost
Ability to achieve ideal costs
Total lead time
D: Delivery
Ability to compete on basis of prompt deliveries
No.1 QCD results in industry
Process transformation
Direct connection to goals
Priority-oriented
Focus resources on key issues
Flexible structure
Seek innovations to strengthen company
Effectively respond to: increased market competition, increased technology sophistication, and changes in business environment
Externally oriented flow
Enhancement of the degree of customer satisfaction
Revitalization

FIGURE 2.3.3 The structure of TP activity and its two basic flows.

Stage 2: Developing Overall Goals into Individual Targets (TP Development). After the establishment of overall goals, TP management turns its attention to the development of individual targets and the plans and actions necessary to achieve them. In the process of developing individual targets, the emphasis must be on clear, concrete plans based on coordination between all departments concerned. Whenever they are encountered, barriers caused by the company organization have to be broken down. The targets are laid out systematically so that they can be understood clearly by each department, and achieved. Then, for the individual objectives at each level (from overall goals to intermediate objectives to individual targets), values are assigned and quantitative contribution factors are calculated.

As each overall goal is expanded into a number of individual targets, ideas are sought from the departments concerned, and a collection of individual plans and activities is organized. Then, a matrix is developed showing goals versus plans and actions. The collections of plans/activities are listed on the vertical axis, while individual targets are listed on the horizontal axis. This matrix is displayed as a chart, called the TP development chart, which is then used in the process of developing specific, concrete plans and actions to ensure that nothing has been overlooked. Individual targets are examined, and the matrix serves to highlight cases where the targeted improvement level cannot be achieved by means of the plans and actions listed thus far. In such cases, the targets must be reexamined, perhaps with an eye to adoption of new technology, and further improvement ideas must be sought.

Based on the TP development chart and its matrix of targets/approaches, a system is put in place for the execution of the plans and actions, through cooperation among all concerned. In this way, the relationship of management's overall goals, individual targets, and specific plans and actions can be laid out in visible form. The project can be viewed from various perspectives and the contribution of each activity becomes clear to all, as well as the cooperation required between various departments. An important feature of TP management is that it enables the skillful application of many traditional problem-solving techniques such as industrial engineering, value engineering, quality control, preventative maintenance, and so forth. These techniques, applied in combination, enable a total action approach to be launched (see Figs. 2.3.4A–2.3.4D).

Patterns for Approaching TP Management

If we were to classify the companies that have won the TP Prize, given annually to firms in Japan that have effectively adopted TP management, we could see two categories as to the way TP management was introduced. (See Fig. 2.3.5 for a classification of the various patterns of adopting TP management.) One class consists of the companies that over a period of three or four years have introduced TP management in order to (1) build a management system that will embody the firm's business strategy and (2) clarify and solve important problems facing the company.

The second class includes companies that have been conducting activities for a few years to improve the company through innovation, using existing *kaizen* and other conventional productivity improvement programs. They have introduced TP management to ensure that these diverse activities, which were previously unconnected, now directly connect to management goals and produce unified results. Such companies expect to implement TP in one to two years. We call the former class Type A, and the latter class Type B, and they can be further classified into 11 patterns, or avenues, for the introduction of TP management.

Among Type A companies, subtype A-1 companies that focus on customer satisfaction (CS) improvement and subtype A-4 companies that seek ideal cost realization are particularly common. CS improvement companies introduce TP management with the goal of building a CS management system that can coordinate and integrate activities related to Q, C, and D. Companies seeking to realize ideal costs are generally in industries where severe price competition forces them to tackle the challenge of cutting costs by more than 50 percent.

(1) Training program for leaders of TP management introduction program	An educational program for executives and managers focusing on TP management techniques and program operation.
(2) Training for those involved with introduction and implementation of the TP management program	An educational program for clarifying the procedures for implementation of TP management and key points regarding program rollout.
(3) Techniques for organizing TP management programs	These techniques demonstrate how management teams and support structures should be organized to promote the adoption of TP management.
(4) Program for establishing basic policies and strategies related to TP management	This is a program that, based on management policy and midrange plans, positions the introduction of TP management within the corporate management structure and establishes suitable policies.
(5) Program for setting overall goals	A program for setting overall goals, establishing target areas, and addressing the question of improvement of companywide productivity.
(6) Program for translating overall goals into individual objectives (e.g., for each product line)	A process for developing overall goals into individual goals and a system for quantifying goals and objectives at each level.
(7) Techniques for systematizing TP goal development and program implementation.	Methods for creating a structure and implementation rollout plan in order that a variety of activities can be coordinated to achieve corporate goals.
(8) Techniques for creating a master plan for promoting TP management	Methods for creating a master plan coordinated with the company's management priorities and mid- and long-range plans and for expanding the scale of activities in a staged manner.

FIGURE 2.3.4A Content of TP management techniques—program introduction.

(1) Selection techniques for TP themes (in matrix form)	Methods for systemization and procedures for creating a matrix of TP objectives and individual activity themes.
(2) System for organizing themes for individual improvement activities	System for planning the development of activity themes and establishing mutual balance between the many individual themes.
(3) Techniques for creating a TP implementation plan	A method for creating an activity plan with a high degree of "achievability." It seeks to coordinate the many activities to the overall implementation plan.
(4) TP simulation system (used during the planning stage)	Used in the planning stage, this is a "rolling simulation" system designed to provide a breakdown of individual objectives and a forecast of expected results.
(5) System for creating the action plans for individual improvement themes and for reporting achievements	A program for developing a "progress system" to cover the entire process from the creation of action plans for each theme (which, in effect, become subprojects) through the reporting of results.
(6) Technique for creating an equipment investment plan	A system for creating the equipment investment plan/schedule and a method for using it.
(7) Technique for creating manpower allocation plans	A system for creating the manpower allocation plan/schedule and a method for using it.

FIGURE 2.3.4B Content of TP management techniques—program management.

(8)-1 Expansion of TP to sales dept.	A system for expanding TP into areas like service improvement and sales increase.
(8)-2 Expansion of TP to new product planning and development	Profits from expanded product lineup, development, and the sale of new products.
(8)-3 Application of TP to achieving attractive product quality	Identify industry quality standards; achieve superior product image, functions, and performance not found in the products of competitors.
(8)-4 Application of TP to shorten lead times	Coordination of production, sales, and inventory, and total lead time reduction.
(8)-5 Application of TP to prevention of quality degradation and to recurrence of problems	Reduction of defects and customer claims.
(8)-6 Application of TP to reduction of inventory and meeting delivery dates	Eliminate late deliveries and part shortages.
(9)-1 TP for materials issues	Material usage quantities, material specifications.
(9)-2 TP for labor productivity	Applied manpower, production rate, work efficiency, output (earned value) per direct employee.
(9)-3 TP for indirect functions	Indirect staffing level, functions, allocation of work.
(9)-4 TP material procurement and purchasing	Make or buy decisions, cost of parts and materials.
(9)-5 Expansion of TP to affiliated companies	TP activities throughout the group of suppliers and other affiliates.
(9)-6 Expansion of TP to the consumption of resources and other environmental issues	Energy conservation, handling of industrial waste, etc.
(9)-7 Expansion of TP to preventive maintenance	Cost of preventive maintenance and repairs.
(10) Expansion of TP to employee satisfaction (ES, SS)	A method of establishing indicators of employee satisfaction, and a system for developing improvement activities.

FIGURE 2.3.4C Content of TP management techniques—"lateral expansion" of program.

Among Type B companies, certain subtypes are noteworthy. They include B-1 companies, which are TPM-based in that they pursue total productive maintenance (TPM), and B-3 companies, which are involved in direct cost/factory cost from total cost.

TPM-based companies, while continuing to pursue TPM activities, typically introduce TP management into the seventh step of TPM, which is autonomous management, and aim to raise the level of such management to the point where the result of each improvement activity directly advances management goals.

PROCEDURES FOR ADOPTING AND ADVANCING THE USE OF TP MANAGEMENT

Basic Steps of TP Management

The procedures for promoting TP management differ to some extent according to the characteristics of each company and how it manages the program. General basic steps are shown

(1) Techniques for evaluating the level of achievement of overall goals	A method of evaluating the extent of improvement and the level of achievement of overall goals, and a system for displaying the connection to company financial results.
(2) Techniques for managing the progress of TP improvement activities	A method for managing the progress of the project against the plan, and a results-monitoring system which enables quick response.
(3) Techniques for monitoring the progress in cost reduction for each cost element	A method for managing the progress of the project against the plan, and a results-monitoring system which enables quick response.
(4) System for reporting progress in the implementation of individual improvement activities	Procedure for reporting progress in implementing individual TP themes (improvement activities) and evaluation method.
(5) TP simulation system (evaluation stage)	
• Monthly calculations for factory management and monthly equipment efficiency report • Monthly labor productivity report and monthly report on meeting delivery dates • Monthly quality reports	• TP simulation system used at the stage of goal revision and evaluation • System for "rolling management" for quick and accurate response and maintenance of a leadership position

FIGURE 2.3.4D Content of TP management techniques—completion and evaluation.

in Fig. 2.3.6. In practice, these 16 basic steps of TP management are adapted to capitalize on the strong points of the individual company. In addition, to achieve important objectives, TP management programs must be organized to involve the entire organization.

The 16 basic steps of TP management programs tend to evolve in five major stages: (1) preintroduction preparation, (2) program launching, (3) program implementation, (4) acceptance and refinement, and (5) competition for TP Prize. Because TP management is particularly tied to a company's management policy and business strategy, which in turn are based on management's vision, commitment and guidance from top management are essential for success. For this reason, it is important that from the earliest (preparation) stages, top management demonstrate its commitment to the program.

Since TP management belongs uniquely to each company that adopts it, there can be no single standard way of application. Instead, each company must create its own management style founded on standard basic steps, but matched to that company's unique situation. Generally, it takes a company two to three years from step 1, announcement of its TP program, until it is ready for step 16, competing for the TP Prize.

KEY POINTS IN THE ROLLOUT OF TP MANAGEMENT PROGRAMS—CASE STUDIES

Case Study 1: TP Program Based on Structural Innovation (Company A)

TP management is actively adopted at 10 factories of Company A.

Background of TP Management Introduction. For any major corporate improvement program to succeed, all divisions of the company and all employees must work cooperatively. In manufacturing companies with several factories scattered throughout the country or in sales

A) Approaches aimed at achieving corporate goals

Programs of this type clarify and solve high-priority business problems. They improve management systems to achieve business goals. Such programs are typically motivated by one of the following five business objectives:

Type	Objective	Approach
A1	Enhancement of customer service (CS)	Build a CS management system to integrate improvement activities related to Q, C, D.
A2	Making products more appealing to customers	Build a management system to achieve product quality which will be attractive to customers . . . a TP management system which focuses on Q.
A3	Enhancement of response time	Build a management system which can achieve lead times superior to competitors . . . a TP management system which focuses on D.
A4	Realization of "ideal cost"	Build a management system which can achieve the ideal cost target . . . a TP management system which focuses on C.
A5	Strengthening of sales power	Create a sales TP system, directly aimed at increasing sales.

B) Strengthening of management capabilities

Programs of this type start from ongoing *kaizen* and productivity improvement activities. They build management systems to better obtain "bottom line" results from ongoing improvement activities. Such programs are typically classified according to what improvement program the company has been using.

Type	Tie in with existing program	Approach
B1	TPM-based programs	While continuing TPM activities, build a management system which better connects those activities to business results.
B2	Programs tied to development of JIT	Build stronger manufacturing capability which directly relates to strengthening product competitiveness, primarily through JIT.
B3	Transition from direct cost/factory cost mentality, and focus on total cost	Breaking away from a mentality focused solely on direct costs and factory costs, build a companywide capability for improving profits through continuous, integrated "total cost reduction."
B4	Programs based on structural revitalization	Achieve the #1 position in the industry by fully realizing the benefits of an ongoing program for structural revitalization of manufacturing.
B5	Programs based on "management by policy"	Develop and manage policies to achieve management objectives. Connect ISO activities to the management objectives.
B6	Programs based on unified cooperation with suppliers and customers	Pursue quality, delivery, and cost improvement through unified cooperation with suppliers and customers.

FIGURE 2.3.5 Eleven avenues for introduction of TP management.

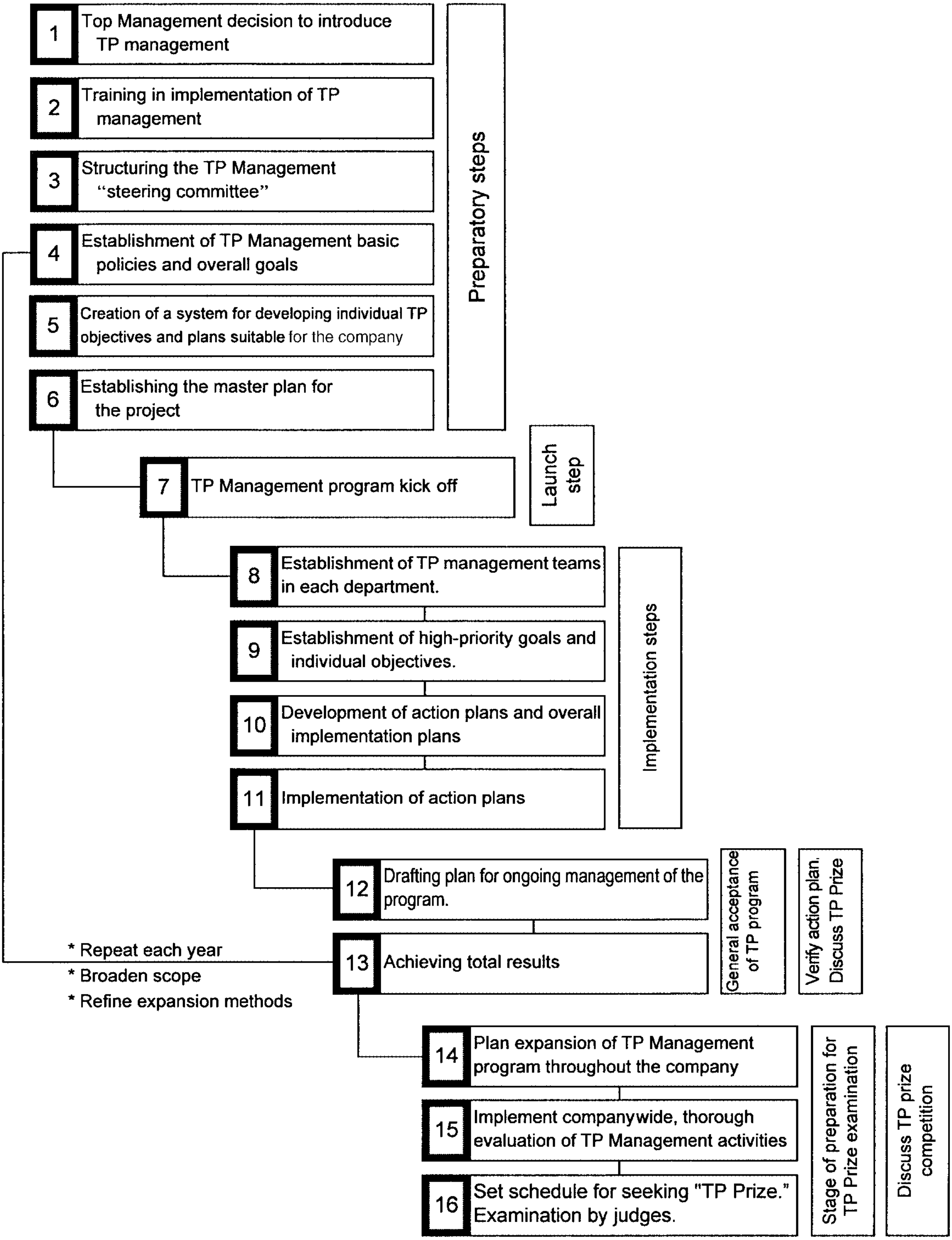

1 Top Management decision to introduce TP management
2 Training in implementation of TP management
3 Structuring the TP Management "steering committee"
4 Establishment of TP Management basic policies and overall goals
5 Creation of a system for developing individual TP objectives and plans suitable for the company
6 Establishing the master plan for the project
Preparatory steps
7 TP Management program kick off
Launch step
8 Establishment of TP management teams in each department.
9 Establishment of high-priority goals and individual objectives.
10 Development of action plans and overall implementation plans
11 Implementation of action plans
Implementation steps
12 Drafting plan for ongoing management of the program.
13 Achieving total results
General acceptance of TP program
Verify action plan. Discuss TP Prize
* Repeat each year
* Broaden scope
* Refine expansion methods
14 Plan expansion of TP Management program throughout the company
15 Implement companywide, thorough evaluation of TP Management activities
16 Set schedule for seeking "TP Prize." Examination by judges.
Stage of preparation for TP Prize examination
Discuss TP prize competition

FIGURE 2.3.6 Basic steps of TP management.

organizations with many offices, such coordination may be difficult to achieve. Even though improvement activities are adopted on a companywide basis, there may be a big difference from location to location in the degree of employee commitment to the program.

This case study introduces the experience of a manufacturer of construction materials (Company A) as it introduced and rolled out a TP management program.

Company A, for the previous 10 years, had engaged in various improvement activities. These included autonomous improvement activities through small group activities and the use of management by objectives, which was implemented down to the individual employee level. Responding to a sharp upward trend in the economy, the company tackled productivity improvement activities, which focused on themes such as increasing production output and improving adherence to shipment schedules. However, following the bursting of Japan's so-called bubble economy, the cooling down of the construction industry resulted in a severe situation for Company A. Under the resulting conditions of no growth and downward pressure on earnings, it became necessary to make major increases in productivity, but that could not be done relying only on the existing improvement activities.

In this situation it was decided to introduce TP management. The objectives were to put to use the total power of the entire company, clarify high-priority management themes, and create a management structure that would enable accomplishment of management goals even under conditions of zero growth. As for the improvement activities that were already being implemented, they were strengthened and expanded.

This is a fully developed example of TP introduction pattern B-4: structural revitalization type, which is one of the 11 avenues for adoption of TP management. It seeks full-scale, broadly developed structural reform of the production function, based on existing activities, such as *kaizen* programs and other productivity improvements programs.

At Company A, the TP management program was launched as a key element in a management policy aimed at raising the level of customer satisfaction and improving the competitive power of its products in terms of Q, C, and D. In phase 1, focusing on the production division, Company A chose four model factories and pursued the theme of creating a competent factory and succeeding in the world market through superior cost competitiveness. In phase 2, a master plan of promotion was drawn up and a program launched with the objective of expanding TP management to all 10 of the company's factories throughout the country. In this phase the program was even extended to overhead divisions associated with the company's head office. The goal was to build a business that can win in today's competitive market. (Company A's master plan is shown in Fig. 2.3.7.)

Rapid Expansion of TP at 10 Factories Countrywide. It is not easy for 10 factories, spread across the country, to keep in step and achieve important advances in management effectiveness in a short time. Even if a TP management program is introduced, the products produced, the production scale, and the problems faced by each factory are naturally different. The following points summarize the experience of Company A in rolling out its TP program.

Point 1: The Company President Announced the Decision to Introduce TP Management. The president gathered all employees of middle-management level or higher from throughout the country for a special TP management kickoff meeting at which he explained the company's current business environment, management's goals, and the process for launching the TP program.

In regard to achieving the company's management goals, the president stated clear concrete numerical targets—for example, the goal of a 30 percent reduction in production cost in three years. By announcing definite time limits, he clearly showed the company's determination. Moreover, to ensure that his message reached all employees, it was presented in the company newsletter and was a topic of high priority whenever he visited a factory. Through such direct and indirect means, the president sought to make all employees aware of the importance of the TP program.

At the beginning of any program, it is important that the company president (or other top manager) personally and clearly announce the company's decision to introduce TP manage-

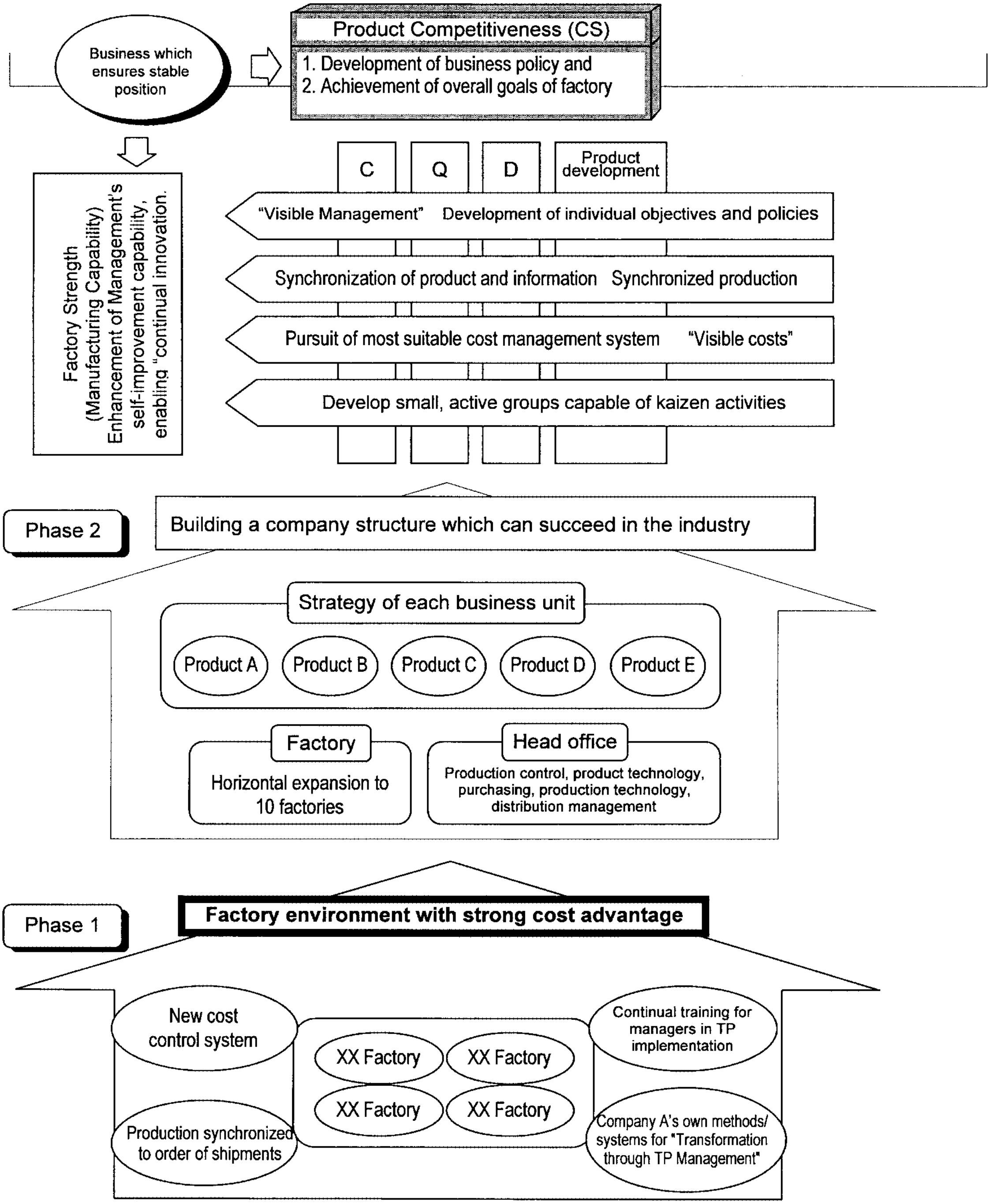

Business which ensures stable position
Product Competitiveness (CS)
1. Development of business policy and
2. Achievement of overall goals of factory
C
Q
D
Product development
Factory Strength (Manufacturing Capability) Enhancement of Management's self-improvement capability, enabling "continual innovation.
"Visible Management" Development of individual objectives and policies
Synchronization of product and information Synchronized production
Pursuit of most suitable cost management system "Visible costs"
Develop small, active groups capable of kaizen activities
Phase 2
Building a company structure which can succeed in the industry
Strategy of each business unit
Product A
Product B
Product C
Product D
Product E
Factory
Horizontal expansion to 10 factories
Head office
Production control, product technology, purchasing, production technology, distribution management
Phase 1
Factory environment with strong cost advantage
New cost control system
Production synchronized to order of shipments
XX Factory
XX Factory
XX Factory
XX Factory
Continual training for managers in TP implementation
Company A's own methods/ systems for "Transformation through TP Management"

FIGURE 2.3.7 Company A's master plan.

ment. Without this endorsement, the critical energy that comes from the fusion of top-down and bottom-up action cannot be obtained.

Point 2: Building an Organization for Effective Promotion of Factory-level and Head Office Goals. Following management policy, general objectives are established at each factory. Targets for the year and individual targets are set, and plans and actions to achieve them are developed. Then, development of the TP program proceeds as follows: (1) accomplish the plans and actions that have been individually set, (2) manage progress at each step, (3) achieve the targets, and (4) gain the expected overall results for the company.

A support office for the project is set up in the head office of the production department. Its function is to provide support to each section of the production department and to the 10 factories as they move ahead with TP management. At each factory, the plant manager is designated to be responsible for promoting the program, while each section chief is responsible for the important activities and objectives assigned to him or her.

The role of the support office is to coordinate all the TP activities of the factories and standardize the formats and procedures used for developing objectives into targets, creating specific action plans, and managing the progress of the execution of the program. Of course, it also actively gives advice on the specific usage of formats, the setting of targets, and the selection of action plans—and in general keeps activities at the various factories moving ahead.

The important companywide priorities for achieving structural innovation, shown in Fig. 2.3.8, are embraced as common study subjects for all the factories.

Goals that involve other departments, such as the goals of design value engineering (VE) and improvements in head office purchasing, are designated as head office goals. Good coordination is needed so that the TP process of target development (i.e., establishing individual targets for various groups within the organization) can be done efficiently. Assignments are made as to which product lines at each factory are to be addressed initially. If there are goals that are common to several factories, responsibilities are allocated among the factories. In this way, important points receive attention and the company's power is used to its maximum effectiveness. This is a clear merit of the companywide coordination aspect of TP management programs.

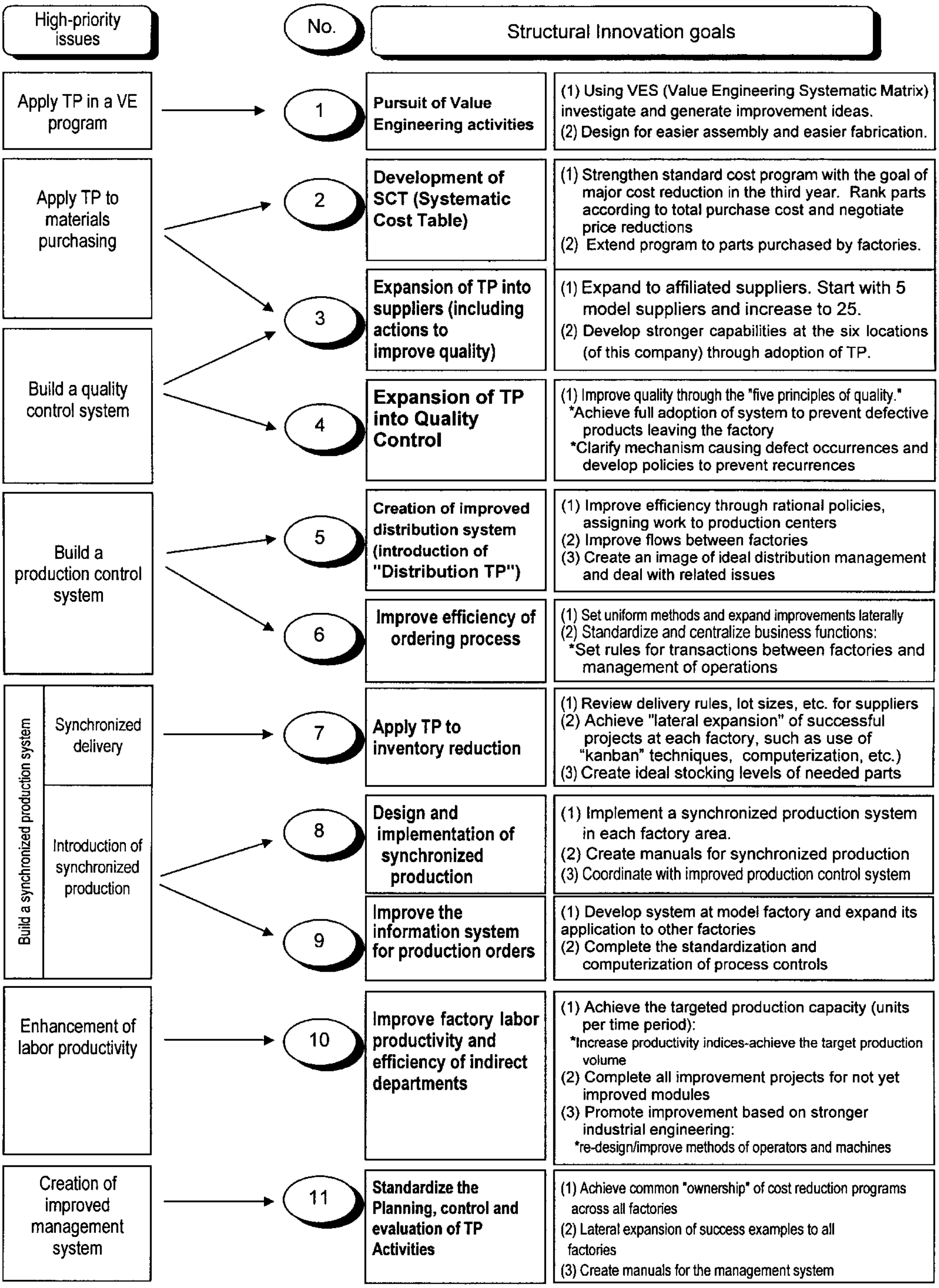
Point 3: Preparing Systematic Steps and Tools for TP Rollout. At Company A, introduction of TP management was divided into seven major stages—from the preparation stage to the final stage (acceptance by all employees and refinement). Within these stages, 28 basic steps were defined for promotion of the program, as shown in Fig. 2.3.8. Each year, during the three-year period of the program, a new set of annual goals was tackled. Each year the scope of these goals became broader and deeper, and the height of the targets began to approach the image of how things should be, which had been laid out in the company's original overall goals.

An additional benefit of the program was that the company's systems were strengthened. The support office identified management techniques (often from the fields of IE, VE, QC [quality control], and so on), which had proven useful in developing concrete action plans, and prepared a manual, sharing these successes with other departments and explaining how the techniques could be applied.

While recognizing the uniqueness of each factory, TP management avoids confusion by introducing uniform thinking and common language—a standardized way of viewing issues. This is essential, since a key goal of TP programs is gradual horizontal expansion of the program throughout an organization. Figure 2.3.9 shows a multiyear program for adopting TP management throughout a complex organization.

Point 4: Sharing Information for Major Companywide Improvement. In the past at Company A, improvement activities had been conducted by each factory, considering only its own situation. The targets seemed to be based simply on what was known to be achievable, such as an increase of x percent year after year, and activities were selected to achieve such unambitious goals.

In contrast, with TP management, the targets of each factory and the themes of its action plans all become clearly visible. The support office gathers concrete information on these improvement plans, right down to the tool and jig level, and shares that information with all the factories so they can use it in their own programs. For example, when purchasing items for



High-priority issues	No.	Structural Innovation goals	
Apply TP in a VE program	1	**Pursuit of Value Engineering activities**	(1) Using VES (Value Engineering Systematic Matrix) investigate and generate improvement ideas. (2) Design for easier assembly and easier fabrication.
Apply TP to materials purchasing	2	**Development of SCT (Systematic Cost Table)**	(1) Strengthen standard cost program with the goal of major cost reduction in the third year. Rank parts according to total purchase cost and negotiate price reductions (2) Extend program to parts purchased by factories.
Apply TP to materials purchasing; Build a quality control system	3	**Expansion of TP into suppliers (including actions to improve quality)**	(1) Expand to affiliated suppliers. Start with 5 model suppliers and increase to 25. (2) Develop stronger capabilities at the six locations (of this company) through adoption of TP.
Build a quality control system	4	**Expansion of TP into Quality Control**	(1) Improve quality through the "five principles of quality." *Achieve full adoption of system to prevent defective products leaving the factory *Clarify mechanism causing defect occurrences and develop policies to prevent recurrences
Build a production control system	5	**Creation of improved distribution system (introduction of "Distribution TP")**	(1) Improve efficiency through rational policies, assigning work to production centers (2) Improve flows between factories (3) Create an image of ideal distribution management and deal with related issues
Build a production control system	6	**Improve efficiency of ordering process**	(1) Set uniform methods and expand improvements laterally (2) Standardize and centralize business functions: *Set rules for transactions between factories and management of operations
Build a synchronized production system: Synchronized delivery	7	**Apply TP to inventory reduction**	(1) Review delivery rules, lot sizes, etc. for suppliers (2) Achieve "lateral expansion" of successful projects at each factory, such as use of "kanban" techniques, computerization, etc.) (3) Create ideal stocking levels of needed parts
Build a synchronized production system: Introduction of synchronized production	8	**Design and implementation of synchronized production**	(1) Implement a synchronized production system in each factory area. (2) Create manuals for synchronized production (3) Coordinate with improved production control system
Build a synchronized production system: Introduction of synchronized production	9	**Improve the information system for production orders**	(1) Develop system at model factory and expand its application to other factories (2) Complete the standardization and computerization of process controls
Enhancement of labor productivity	10	**Improve factory labor productivity and efficiency of indirect departments**	(1) Achieve the targeted production capacity (units per time period): *Increase productivity indices-achieve the target production volume (2) Complete all improvement projects for not yet improved modules (3) Promote improvement based on stronger industrial engineering: *re-design/improve methods of operators and machines
Creation of improved management system	11	**Standardize the Planning, control and evaluation of TP Activities**	(1) Achieve common "ownership" of cost reduction programs across all factories (2) Lateral expansion of success examples to all factories (3) Create manuals for the management system

FIGURE 2.3.8 Important issues at the factory levels and structural innovation goals.

TOTAL PRODUCTIVITY MANAGEMENT

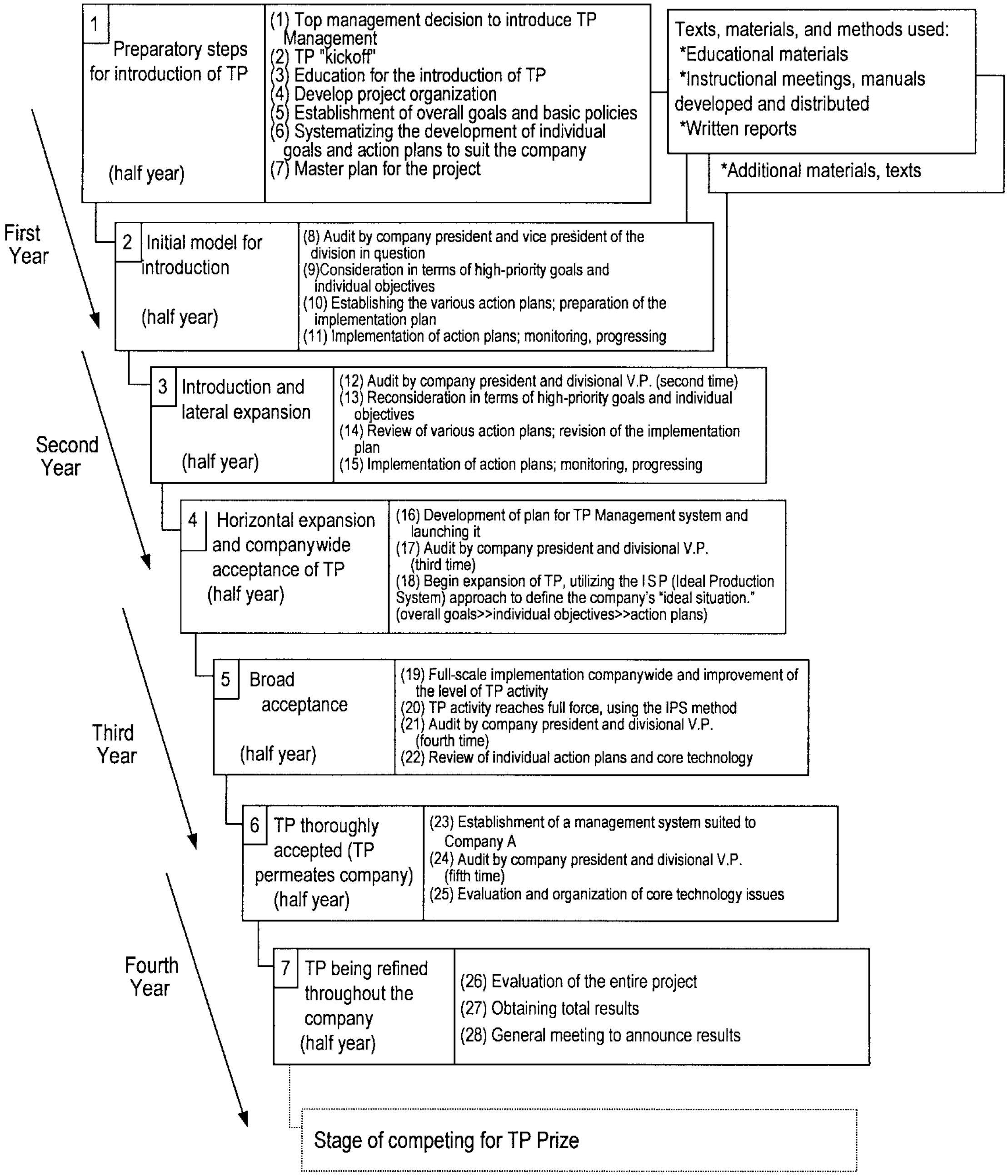

1 Preparatory steps for introduction of TP (half year)
(1) Top management decision to introduce TP Management
(2) TP "kickoff"
(3) Education for the introduction of TP
(4) Develop project organization
(5) Establishment of overall goals and basic policies
(6) Systematizing the development of individual goals and action plans to suit the company
(7) Master plan for the project
Texts, materials, and methods used:
*Educational materials
*Instructional meetings, manuals developed and distributed
*Written reports
*Additional materials, texts
First Year
2 Initial model for introduction (half year)
(8) Audit by company president and vice president of the division in question
(9)Consideration in terms of high-priority goals and individual objectives
(10) Establishing the various action plans; preparation of the implementation plan
(11) Implementation of action plans; monitoring, progressing
Second Year
3 Introduction and lateral expansion (half year)
(12) Audit by company president and divisional V.P. (second time)
(13) Reconsideration in terms of high-priority goals and individual objectives
(14) Review of various action plans; revision of the implementation plan
(15) Implementation of action plans; monitoring, progressing
4 Horizontal expansion and companywide acceptance of TP (half year)
(16) Development of plan for TP Management system and launching it
(17) Audit by company president and divisional V.P. (third time)
(18) Begin expansion of TP, utilizing the ISP (Ideal Production System) approach to define the company's "ideal situation." (overall goals>>individual objectives>>action plans)
Third Year
5 Broad acceptance (half year)
(19) Full-scale implementation companywide and improvement of the level of TP activity
(20) TP activity reaches full force, using the IPS method
(21) Audit by company president and divisional V.P. (fourth time)
(22) Review of individual action plans and core technology
6 TP thoroughly accepted (TP permeates company) (half year)
(23) Establishment of a management system suited to Company A
(24) Audit by company president and divisional V.P. (fifth time)
(25) Evaluation and organization of core technology issues
Fourth Year
7 TP being refined throughout the company (half year)
(26) Evaluation of the entire project
(27) Obtaining total results
(28) General meeting to announce results
Stage of competing for TP Prize

FIGURE 2.3.9 Basic steps for a TP management project.

the factories, each purchasing manager benefits from a crib sheet showing the name of the supplier for each item, the price charged to each factory, and the purchasing terms. Moreover, if there are concrete action plans for improvements in purchased parts or cases where price reductions have been achieved, that information is also shared. In the past, the climate was one of subtle competition among the factories, and know-how was not shared.

Likewise, in the past, factory employees seldom visited other factories. With the introduction of TP management, however, employees were encouraged to visit other factories and exchange information, and such activity became quite brisk. Now, the mission of each factory has changed from “create a factory that is better than other factories” to “create a factory that is the best in Japan, or even in the world.”

Point 5: Audits by Top Management at Key Milestones in the Project. As described in the previously mentioned 28 basic steps, top management audits of the TP management program are performed by the president and general manager of the department at the beginning and midpoint of each business year. The effort of top management in visiting the 10 factories to perform these audits every six months, right from the start of the TP program, reflects the high level of management interest. This also provides top management a chance to make a direct appeal to factory employees to undertake activities enthusiastically and achieve results. In a sense, these top management audits are one of the company’s targets and much energy is concentrated on making them effective. For each factory, an audit becomes something of a “festival,” the largest event of the year, with all employees taking pride in displaying their TP achievements.

Point 6: Production Process Improvement Involving Related Companies. Except for unusual cases where companies manufacture everything themselves, the pursuit of fundamental improvements throughout the entire production process of a factory must be considered in connection with related companies (suppliers, service providers, etc.) This is particularly true in the case when related companies do their work *inside* the subject factory. This is also true for whatever subject is selected for improvement (e.g., lead time shortening, quality improvement, or cost reduction).

At Company A, first the production lines operated by its own employees were improved. Then, based on the success it achieved (which was reflected in the manual prepared by the support office), management, functioning like an internal consultant, guided and trained the related companies that were in charge of other areas inside the factory. Those suppliers and service providers, in turn, built on the know-how they gained and promoted their own improvement activities. This also contributed to the expansion of TP management inside and outside the factories of Company A.

For true mutual prosperity and mutual survival, related companies also need to achieve fundamental improvements. Many of them face severe conditions where their survival is at stake, and since most of these companies are midsized at best, the spin-off benefits of Company A’s TP program are very valuable in helping them to strengthen their management base.

The Results of Implementing TP Management. Another factory obtained the following results two years after introduction of TP management. Productivity improved by approximately 60 percent and lead time was shortened to about half. These results came from the structural innovation theme, which was one of the main goals focused on as part of the TP program. Specifically, the results came from

- Elimination of wasteful storage and transfers through the reduction of work in process (WIP) inventories maintained on the factory floor between processing areas, which was made possible through the introduction of synchronized production.
- Reduction in waiting time through synchronization of production sequences.
- Improvement in work methods and equipment efficiency through the application of industrial engineering methods.

Quality improved to the extent that the number of customer claims was reduced to less than half. There were significant yield improvements, as well (see Fig. 2.3.10).

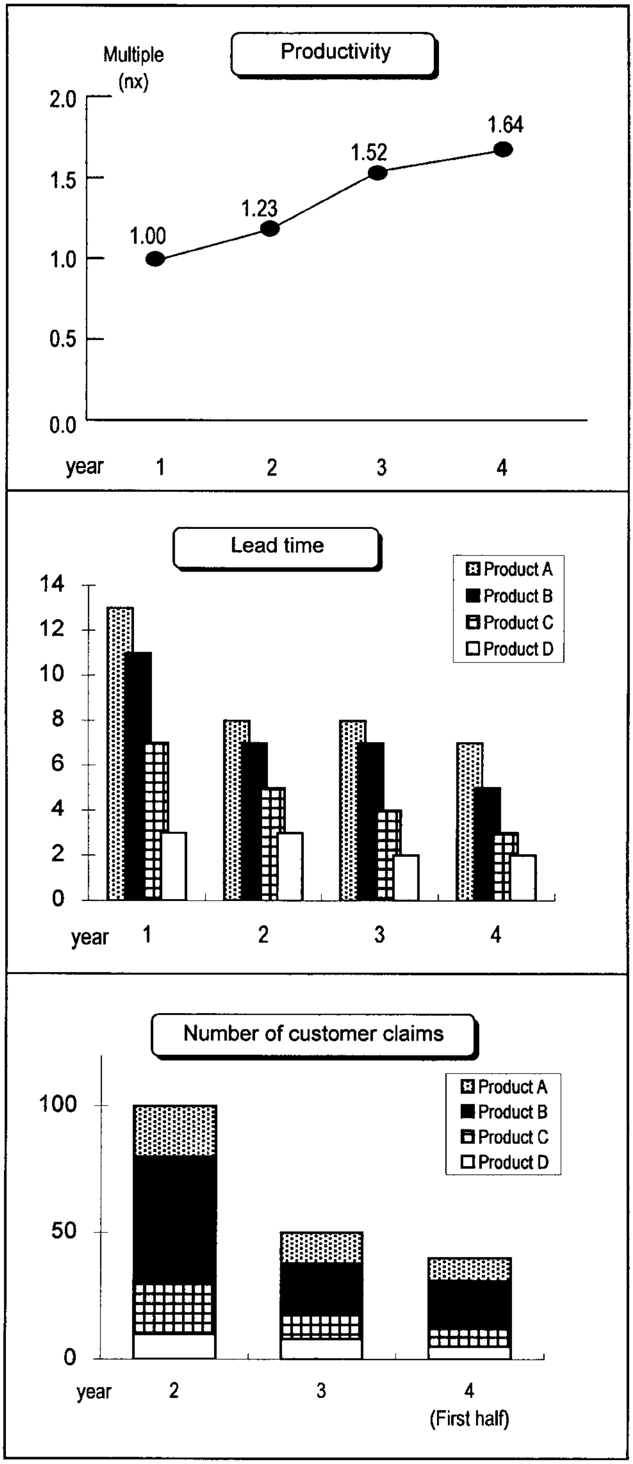


FIGURE 2.3.10 Results after TP management introduction.

Comparing the various factories as they proceeded to adopt TP management, initially the difference in level between the factories (measured by various scales) was large. However, as all the factories progressed with fundamental improvements to their structure and operations, this variation became much less. Companies compete in their given industry according to the competitive power of their products, and in principle, competition between a company's own factories is inappropriate. However, the following comparison of factories provides a visualization of the degree of progress of the total TP program. When factories recognize the accomplishments of each other, they may stimulate competition in a positive sense (see Fig. 2.3.11).

In addition, the TP program resulted in qualitative improvements:

- Through top-down and "middle-up" promotion, clear objectives and targets are developed. Thorough and detailed action plans are developed that are understood even at the operator level. Clear goals and the ability to confirm results build confidence and foster an atmosphere of trust among all employees involved.
- Rising above the traditional focus on cost reduction alone, employees were shown broader goals such as, "This is the factory we want to be." The position of program elements such as this year's activity and each individual employee's activity and their relationship to the broad goals could then be clearly understood.
- Talented employees from the middle ranks (section manager and subsection manager) were trained and their management skills in such areas as leadership and goal setting were strengthened. New talent was discovered and cultivated among employees, and the competitive strength of the whole organization was increased.

Subjects Requiring Further Work. Initially, TP management was promoted mainly by the head office of the production department. From now on, however, TP will be expanded to address production department relations with upstream functions such as sales, product development, construction operations done by related companies (i.e., users of Company A's products), and service.

To compete effectively in the business of providing construction materials, it is necessary not only to increase the level of customer satisfaction among end users, but also to improve the level of service to first-tier users: construction companies. To raise the satisfaction level among downstream affiliates, Company A must seek further improvements such as practical packaging and the creation of product sets that suit the users' needs on construction sites. To accomplish these goals, the scope of involvement in TP management must be extended to other departments as well.

At the factories, management is concerned about its response to the trend toward an older workforce and an increase in the number of female employees in the future. For example, to achieve a "comfortable" factory, ergonomic techniques will have to be applied to improve work methods and address environmental issues. In this way, Company A plans to promote an even higher level of structural reform.

Case Study 2: The Sales/Product Development Type of TP Program (Company B)

The next case is an example of TP management implementation that started from the opposite end of the business—from sales strategy. The focal point of this program was a new product strategy, and it provides an example of promoting TP management with total company involvement, including the sales and product development departments and the factory.

Company B manufactures hot water heaters and other heating units for residential use. It is a medium-sized company in its industry and sells through distributors located throughout the country. Under conditions of severe price competition, the company was surviving through cost reduction activities at the factory. Its objective was to increase market share, and to do that the following activities were initiated.

TOTAL PRODUCTIVITY MANAGEMENT

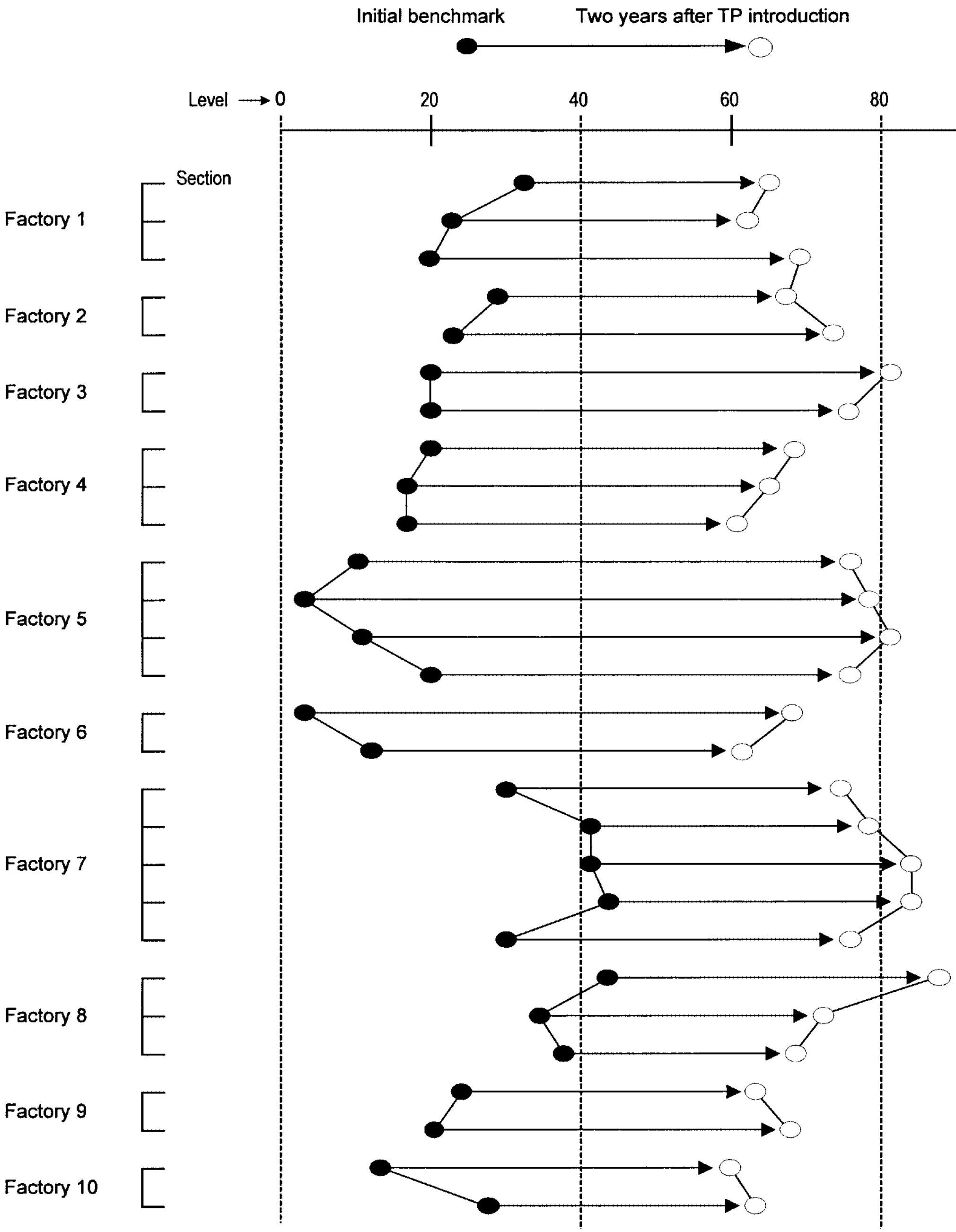


FIGURE 2.3.11 TP program achievements in each factory.

At first, starting from midrange management goals, market share targets for each product were established, and product distinction strategies (price/function/service) for each geographic area and customer segment were developed. The program thus started at the stage of formulating the basic marketing strategy.

Next, members were gathered from each involved department and the plans for each product were discussed. The finalized plans were organized as a "sales promotion catalog" for the future, and specific targets for product features were established. Through this effort, each involved department determined the goals and activities it needed to accomplish for success in the market. In this way, a common understanding of the total project was achieved.

Based on the finalized plans, the sales and product development departments began joint activities. A TP development chart was prepared so that the technical development activities needed for the new products and the strategic goals for sales promotion and sales channel development could be managed in parallel (see Fig. 2.3.12). At this stage it became necessary to coordinate with the factory concerning product costs.

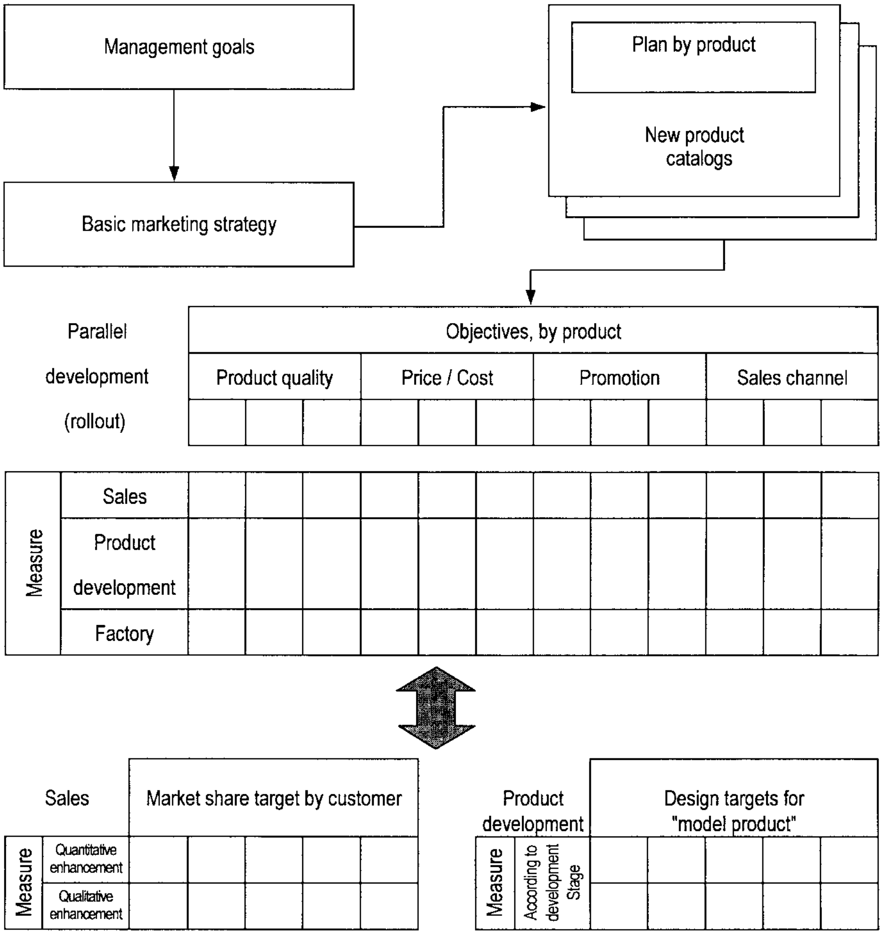

Management goals
Basic marketing strategy
Plan by product
New product catalogs
Parallel development (rollout)
Objectives, by product
Product quality
Price / Cost
Promotion
Sales channel
Measure
Sales
Product development
Factory
Sales
Market share target by customer
Measure
Quantitative enhancement
Qualitative enhancement
Product development
Design targets for "model product"
Measure
According to development Stage

FIGURE 2.3.12 Outline for expansion of TP program in sales and product development department.

In addition, both the sales department and the product development department set individual goals for themselves, which they then pursued in earnest. In the sales department, clear targets for the company's market share were established for each area and customer. Then, the sales plans and actions necessary to achieve that share were developed for each major customer, both in quantitative terms (number of sales calls, timing, person to be visited) and qualitative terms (proposal-oriented sales, sales techniques). Meanwhile in the product development department, application of TP management resulted in a development process characterized by use of concurrent engineering and coordination with the factory regarding cost planning and design of the production process.

For new product development programs, in addition to the TP development chart, a single page, companywide development schedule was created. This enabled coordinated management of the various action plans and the progress of the departments involved.

As sales and product development departments energetically pursue TP management activities, key points to remember are to:

- Establish product targets based on a clear product strategy.
- Have employees, in particular the middle management category, participate in the TP management program as much as possible so that they can fully understand and appreciate the meaning of the goals of top management, from a more managerial viewpoint.

In addition, by establishing their respective targets almost simultaneously, the sales and product development departments gain a sense of teamwork and can promote related activities in a truly united manner. "Walls between departments," that old nemesis, can be torn down.

Through procedures and techniques described previously, top management's strategic goals are converted into plans and actions that reflect management's sense of values and desire to promote these goals throughout the organization. This is another major benefit from TP management programs.

A FINAL WORD

TP management is a new system for achieving fundamental improvements throughout complex organizations. It enables a variety of management goals to be pursued concurrently. TP management is not a method of solving specific, isolated problems. Instead it may be called a comprehensive management and control technique aimed at achieving structural improvement in organizations.

FURTHER READING

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BIOGRAPHIES

Yoshiro Saito graduated from the Engineering Research Department of the Shibaura Industrial University and did graduate study in industrial management at Waseda University. He joined JMA Consultants, Inc. (Tokyo) in 1983 and became a senior consultant in 1995. Since 1998 he has been head of the firm's TP Management Consulting Division. He consults in the area of efficiency improvement across a broad range of areas, including factory control systems, purchasing, research, and design. He is also an authority on the optimization of production systems to achieve customer satisfaction. Saito has written several books, including texts on such subjects as improving work in the construction industry, lead time reduction, and inventory management. His research in the field of cost reduction and lead time shortening in build to order businesses won a coveted award from the Ministry of Trade and Industry.

Masanaka Yokota graduated from the Production Engineering Department of Nihon University in 1978. After valuable industry experience, he joined JMA Consultants, Inc. (Tokyo) in 1985. In 1997 he was promoted to senior consultant. Much of his consulting work has focused on management innovation across a spectrum of industries including automobiles, machinery, metals, construction, plastics, textiles, and paper. He has assisted companies to increase the competitive strength of their products in terms of Q, C, and D. He has been active in introducing the MOST method of standard time setting (developed by H. B. Maynard and Company) to Japanese industry, and he is the coauthor of two books on shortening production times. His efficiency improvement work extends beyond the manufacturing area to indirect functions, such as sales, product development, and design.

CHAPTER 2.4

PERFORMANCE MANAGEMENT: A KEY ROLE FOR SUPERVISORS AND TEAM LEADERS

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Performance management is a key role for supervisors and team leaders in the workplace. This role is critical to achieve and maintain gains from improvement initiatives. To be effective, supervisors need a comprehensive approach to performance management, an approach that is practical and designed to be used in the workplace to achieve results through people. This chapter describes such an approach. The Maynard performance management approach provides supervisors with practical guidelines for

- Using standards to understand and manage the work
- Providing conditions for success
- Measuring for feedback
- Taking action to improve

This approach is presented through a model that serves as a framework to illustrate and link the key components.

INTRODUCTION TO PERFORMANCE MANAGEMENT

General Definition

Performance management is a management approach used to help an organization achieve its goals through people. In its typical application, a manager and an employee agree to performance objectives that the employee will work to accomplish throughout the year. These objectives support the organization's goals and developmental needs of the employee with the purpose of getting the right things done and motivating employee success. The employee's achievement is then measured and used for further developmental plans and often as a criterion for decisions on pay and promotion. It makes sense that this process of setting objectives and measuring performance would improve an organization's probability of success.

The Maynard Performance Management Model

The Maynard model, outlined in this chapter, provides an approach to performance management that frontline supervisors or team leaders can use on the job every day (the term supervisor will be used throughout this chapter). This is a unique approach to performance management that provides practical advice on facilitating employee performance, one of the most challenging parts of the job. The approach, based on sound management principles, encourages supervisors to

- Know the work
- Provide conditions for success
- Measure for feedback
- Take action to improve

This formula is represented by a performance management model (Fig. 2.4.1) that depicts these elements and their relation to each other toward the goal of improving productivity.

Standards	Use standards to define the work. What are we trying to accomplish? What methods ensure the best quality, efficiency, and safety? How many people do we need to get it done? How long will it take? Standards give the answers.
Action	Provide conditions necessary for employees to be successful.
Productivity	Strive for improved productivity. Continue to improve the relationship of resources input to results achieved.
Feedback	Provide feedback. Feedback is information from the work to help those doing the work know how they are doing.
Action	Take action to conform and improve. Employees and supervisors respond to feedback with action to do better in the next cycle.

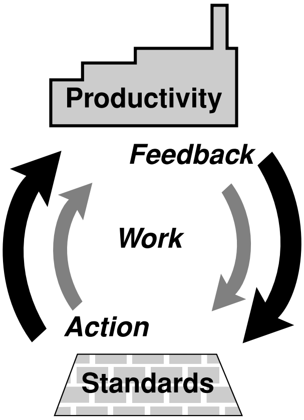


FIGURE 2.4.1 The Maynard performance management model.

The approach is a practical, straightforward, commonsense way to manage people. To use this approach, a supervisor needs to

- Define what employees need to do.
- Give them what they need to do it.
- Let them know how they are doing.
- Help them do what is needed, change what is wrong, fix what is broken, and provide what is not there.

Despite the simplicity, many supervisors do not approach managing employee performance in this way. In many cases, they simply do not have adequate time. Time is the limiting factor for supervisors because they are in a pivotal place in the organization. They feel pressure to get product out the door, rivaled only by the demand of overseeing and coordinating the efforts of the employees who do the work. Often they find that their time is taken up by tasks such as expediting customer orders, filling out paperwork, and meeting with suppliers. The irony is that these activities, although important, leave little time for performance management, an activity that has the potential for consistent payoff in productivity gains.

STANDARDS: A TOOL TO UNDERSTAND AND MANAGE WORK

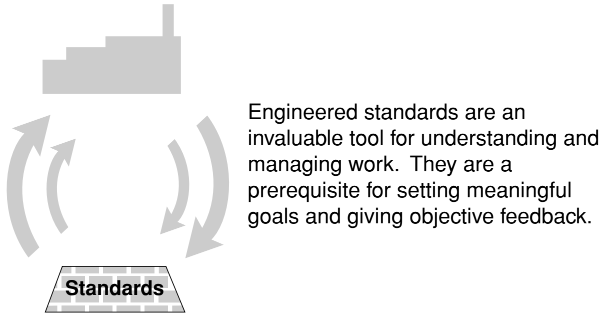
Effective Supervisors

Effective supervisors know the work of their subordinates. Knowing the work, they are able to assign work, explain what needs to be done, and define the goal or measure of success. They make rounds in the workplace, looking at critical points in the operation to evaluate how the work is progressing. They look for clues like work piling up between stations or operations not achieving intermediate goals that indicate problems. They empower employees to do the same. When a problem is identified, they analyze the situation, provide direct feedback to the employees, and encourage their involvement in planning the solution. They ask questions and listen to employees, bringing their experience and skill into the situation. Like a good coach, they know the game (the operation) and their players' skills. Watching the score and the conditions, they devise a game plan to reach the goal. The keys to success for these supervisors are (1) understanding the work, the methods, and the measures, and (2) knowing the employees, their strengths, and weaknesses. How does a supervisor get to this point of understanding and knowledge?

There are two factors that allow someone to become the effective supervisor described previously. The first is *time,* time to get to know the operation, and the employees, and time to be involved in the workplace. The second factor is the availability of *objective measures* upon which to base decisions, strategies, and feedback. Just as knowing the score and the time remaining in the game allows a coach to make the right moves, knowing production goals and having good measures allows a supervisor to make good decisions.

Engineered Standards as a Tool

If the supervisors have the luxury of working in an environment where engineered standards are used, they have an invaluable tool (Fig. 2.4.2). Engineered work standards are inherently objective. They are useful for planning resources, setting realistic goals, measuring performance, and providing feedback.



Engineered standards are an invaluable tool for understanding and managing work. They are a prerequisite for setting meaningful goals and giving objective feedback.

FIGURE 2.4.2 Standards.

Engineered standards should be based on best methods. They should not include any unnecessary motions, nor do they account for nonstandard conditions. They are systematically developed based on an average trained worker, working at a normal pace under normal conditions. An engineered standard tells you how long it should take to perform a work task. Knowing this is basic to planning how much time and how many people it will take to get a job done. The act of developing standards is a commitment to knowing the work and being objective about measurement.

Preparing the Supervisor

Involving supervisors in the work measurement process creates a natural way for them to understand the work and the standards. This involvement greatly accelerates their learning process. If the measurement is done using a Predetermined Motion Time system like MOST®, the analysis itself creates a new way of viewing work—a view that sees work activities as elements with a time component, and a view that makes visible the inefficiencies in work methods. By understanding the work measurement technique, a supervisor can begin to not only understand how the standards are created but also to fully appreciate how changes in method impact the time to perform a job. This heightened awareness makes a supervisor sensitive to method improvement opportunities and provides an objective means for coaching employees to use the prescribed method.

The greater the involvement the supervisors have in measuring work, the better they are able to manage it. To give a supervisor exposure to work measurement, an organization should offer, at minimum, formal appreciation–level training in the work measurement techniques used. In addition, the organization should provide supervisors every possible opportunity to work with industrial engineers and work measurement staff to define the methods and validate the standards. One of the best methods for preparing supervisors to manage work is to provide a two to three month developmental assignment doing work measurement in the industrial engineering department.

Other Benefits of Standards

The benefits of analyzing and measuring work in a detailed way can be extended beyond the level of the supervisor to every employee. When employees analyze and measure their own work, there are "far reaching implications for motivation, self-esteem, balance of power between workers and management, and the capacity of the company to innovate, learn and remember." This is what Paul S. Adler wrote about NUMMI, the GM-Toyota joint venture in Fremont, California, where employees themselves learned to use work measurement techniques and analyzed, measured, and standardized their own work [1]. To employees involved in the work measurement process, there is no mystery in how standards are developed. They recognize that the best methods should be documented and used consistently to ensure quality and safety. From there it is only a small step to accept a standard time for performing the work and measures to help achieve performance.

There are other benefits to engineered standards in the workplace. In an efficient work measurement process, the work is studied systematically from the top down. When this approach is used, similar tasks from all over the facility are considered and standards are engineered to provide consistent methods and times. This alone makes it easier to teach and learn jobs throughout the facility. In sum, the standardization by engineering methods improves consistency, quality, safety, and efficiency.

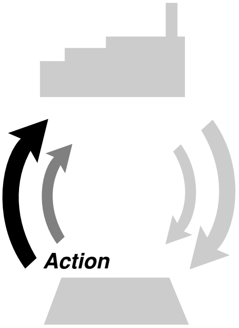
With engineered time standards, supervisors can set objective goals, knowing they are attainable. Armed with knowledge of the work, everything that stands in the way of performing the prescribed method becomes more visible. They can identify nonconformance issues and work to eliminate them. Knowledge of the work gives the supervisors and their employees an objective vantagepoint to view the work environment. From this vantage point, the time it takes to search for a tool, or walk to get a part, takes on new meaning. Strategies to reduce wasted motions are not only more acceptable to employees, they are often self-initiated.

When employees understand and accept engineered standards as the basis of setting goals, the feedback on attainment is meaningful. A goal that is set arbitrarily, and is seen as difficult to attain, does not have the same impact when performance is not achieved.

ACTION: PROVIDING CONDITIONS FOR SUCCESS

Supervisors are measured on what their employees achieve. All their effort does not amount to much if the crew does not get the results needed to satisfy customers. The measure of success of a supervisor is what is accomplished by the people who do the work. It is a supervisor's job to be proactive in providing the conditions necessary for employee success (Fig. 2.4.3). A supervisor has to see what is needed for employees to perform, and then make it a priority to provide it consistently. This is the heart of performance management.

What are the things employees need in order to perform? First, employees need to understand the work and the desired results. They need skills and knowledge to perform. They need resources such as defect-free materials and properly functioning equipment to get the job done. And finally, they need feedback on their performance in order to learn, solve problems, gain confidence, and improve.



It is the Supervisor's job to be proactive in providing the conditions necessary for employees to succeed. Employees need
- An understanding of the work and the desired results
- Training
- Resources (Materials / Equipment / Systems)
- Feedback
- Motivation

FIGURE 2.4.3 Action.

Understanding the Work and the Desired Results

Employees need to know what result is expected and what methods to use to accomplish it. This is a basic premise. The effort to keep employees informed is ongoing. The supervisor needs to establish methods of communication and training that are effective and a natural part of the environment and the working relationship with employees. There are two avenues of communication that the supervisor can use to keep up with employee information needs. These avenues are visual communication (visual information and cues in the workplace) and interpersonal communication (personal exchange of ideas with an individual or group).

Visual Communication. Visual communication is an important tool for supervisors because it gives employees the opportunity to be self-sufficient. Information and instructions are built into the workplace and employees use a self-serve approach for getting data, reviewing procedures, and finding and replacing supplies. The foundation for visual communication is a workplace clear of clutter and excess inventory that obscures the basic operation. A visual workplace helps people know what is going on and what they need to do by letting them see what is happening. The work flows so employees can see their contribution to the overall operation. In addition, visual displays provide information about the important elements of a job like procedures, production goals, and quality checks. Everything in the workplace has a purpose and a specific storage location so it is easily retrieved and stored. Some visual communication strategies include

- *Visual method sheets.* Visual method sheets document the work content of each workstation. They illustrate and identify each task performed at the station using labeled photos, diagrams, or drawings. Operators use visual method sheets as a training tool when they initially learn to perform the work and thereafter as a reference. They are particularly valuable when operators must move between stations or models on a mixed-model assembly line.
- *Visual quality sheets.* Visual quality sheets are similar to visual method sheets, but they focus on the quality control points in the operation. Illustrations are used to show employees what to look for on incoming and outgoing quality checks and highlight proper procedures for operating steps with quality implications.
- *Visual workplace organization.* Visual workplace organization gives everything a place and uses techniques such as labeling, outlining, and color coding to make it easy for anyone to find and replace items quickly. This form of visual communication is usually undertaken after a process (such as 5-S) is used to sort out unneeded items and set up systems for storage.
- *Visual production control.* Visual production control is part of an overall work flow strategy. It can be as simple as posting the production schedule for the shift, or it can involve a more complex system of controlling work and material flow using signals between stations. Basically, employees are informed about what needs to be done and when by visual cues.
- *Visual information display.* A visual information display provides pictorial and graphical displays of key indicators and planning information for a work group. The information displayed is typically selected with input from the work group and is updated by members of the group. It can include information on topics such as productivity, quality, safety, housekeeping, delay time, improvement projects, on-time delivery, changeover time, machine downtime, employee skill development, employee vacation schedule, absenteeism, and so on. The visual information display provides data that lends meaning to various facets of the work.

Interpersonal Communication. Interpersonal communication involves conveying information using voice, facial expressions, and body language that can be understood by another person. It seems simple, but to say it is simple ignores the fact that miscommunication occurs daily—between husbands and wives, parents and children, and supervisors and employees. How then can a supervisor approach this task to minimize the probability of miscommunication?

One way is to approach each communication as a thought transmission. Ferdinand Fournies, in *Coaching for Improved Work Performance,* makes the point that when we communicate what we are actually attempting to do is *transmit thoughts* [2]. We want the receiver to think and internalize what we would like them to know. Often what happens in communication is one person talks and the other reacts with a different thought, rather than fully taking in what is being said. Sometimes it is a defensive reaction, or often it is a thought about what to say next. This is what happens when you are introduced to someone for the first time and promptly forget their name. You hear the name, but immediately react by planning what to say next. The same thing can happen when a supervisor communicates work instructions.

When the information is important, the supervisor needs to consider some alternative ways to communicate the message. Instead of simply telling something, according to Flouries, the key is to say or do something that will cause your idea to form in the other person's mind as a response to what you said or did. This takes some effort on the supervisors' part. First, they must develop a rapport with the individuals to open the lines of communication; then they need to deliver a message that will engage the employee and reinforce important information.

Building Rapport

Building rapport means more than just making small talk; it means making the effort to connect with another person. This connection builds the person's self-esteem by demonstrating interest in them. A supervisor can build a connection by finding common interests with an employee, by using the individual's name frequently in conversation, and by showing genuine interest in the employee's views or pastimes. People enjoy the feeling of camaraderie that develops, which helps to break down barriers to communication.

Delivering a Message

When the information is important, a supervisor needs to be able to get the employees thinking and, ultimately, talking about it. To plan such communication, the supervisor needs to begin with the end: "What do I want the employee to think, feel, and do?" Then, plan an approach that

- Builds rapport
- Clearly states the purpose
- Provides details from the employee point of view (using examples and stories that draw employees into the topic)
- Asks for input and feedback (when employees talk about it, you can gauge transmission)
- Reviews the plan of action

This is a different perspective on communication. Instead of searching for the right words to express a thought, you think of how to get the person to say it. Instead of doing all the talking, supervisors should ask questions and get the employees thinking and talking about what is needed. They should guide the thought process instead of providing all the answers.

This technique of thought transmission can be used in daily instructions, meetings, coaching, and formal training. With it one can reduce the probability of miscommunication or misunderstanding.

Daily Meeting

A brief daily meeting is one way to keep people well-informed about operating issues that affect them. This face-to-face encounter allows a supervisor to build rapport and share what is expected, what is different about today, what happened on the previous shift, and issues that might impact performance. This is a time when the supervisor can review significant observations or trends from a visual information display.

Training

Training job skills is a strategic form of communication. At the conclusion of a training experience, employees must be able to perform safely and effectively. When planning training, start at the end. Define how you will measure skill attainment and develop specific criteria for evaluation. Based on this, you can develop a specific plan for training. Ask, "What does the employee need to do successfully when the training is completed?"

Use a training strategy that involves the employees actively in the learning process. The more senses they use, the greater the retention. Plan for immediate application of new skills.

Basic Training Methodology. Break training into logical components. Do not attempt to take on the job as a whole. Consider both what the employee needs to do (procedures) and what understanding is needed (hidden mental skills) to do the job. Training to this understanding level will pay off with a shorter overall learning curve and ultimately better decisions in the operation. For each logical component of training

1. *Prepare the employee.*
   Explain what and why. Use visual aids where possible. Check understanding.
2. *Demonstrate the task.*
   Show the employee how to perform the work. Check understanding.
3. *Let the employee try.*
   Depending on the nature of the job and the consequences of a mistake, you may want to have them explain each step before they do it.
4. *Let the employee review his or her own performance.*
   Observe carefully and provide feedback and clarification as needed.
5. *Allow application of new skills.*
   Provide opportunity for practice as soon as possible after learning.

This simple training strategy is effective because it involves the employee actively and addresses the different learning styles: visual (seeing it), auditory (hearing it), and kinesthetic (doing it).

Resources

While knowing the work and the desired results is important for employee performance, it is only one variable in the performance puzzle. Employees need resources to get the job done. It is a helpful exercise for a supervisor to list the things employees need to successfully do their job (Fig. 2.4.4).

What happens if one or more of these factors are not present at any point in time? Employees cannot perform at the required rate. When a supervisor works hard to provide the conditions and external factors necessary to perform at the required rate, it not only allows the employees to do the job, it communicates that the required rate is important to achieve. The message is clear: We need to get it done.

How can a supervisor stay on top of all the external factors needed in the workplace? By being proactive. According to Steven Covey's best-seller *The Seven Habits of Highly Effective People,* this means taking responsibility and initiative to make things happen [3]. It requires being resourceful and creative, exerting energy on the things you can do something about.

PERFORMANCE MANAGEMENT: A KEY ROLE FOR SUPERVISORS AND TEAM LEADERS

- *properly running equipment*
- *materials (defect free)*
- *tools (correct and available)*
- *systems for production control and material storage and retrieval*
- *fixtures*
- *supplies*
- *information and reporting systems*

FIGURE 2.4.4 Resources.

One supervisor, trying to create an organized workplace, wanted to provide holders for rolls of stickers employees used frequently on the job. On her own time, she bought toilet paper holders from a discount department store and had maintenance install them at the workstation. This small gesture communicated volumes to workers about the importance of their work and the organized workstation.

While supervisors are creating the circumstances that allow employees to be successful, they should tell them that this is their role—not to do the job for them, but to help them do the job successfully.

Feedback

Employees need to be clear on roles. They need to know what is expected from them and if they are meeting the expectation. This is where feedback comes into play. One indication to employees that achieving the required performance is *not important* is that they do not get regular feedback on how they are doing. Larkin and Larkin in their article, "Reaching and Changing Frontline Employees" in *Harvard Business Review,* make the point that employees recognize what an organization values by what drives its decisions and by what it measures [4]. For example, if you are a general manager in a retail store and you say customer service is the most important value, then turn around and schedule the staff by an arbitrary budget constraint rather than by the volume of work needed to adequately serve the customer, employees perceive that budget is actually more important than customer service—and they are right.

You need to measure and act on what you *value.*

Motivation

A supervisor needs to be aware of the factors that influence employee performance. For the most part, employees behave in a way they feel is logical for a situation. The fact that the behavior itself may actually be illogical may reflect more the employee's limited point of view rather than a conscious choice to be illogical. It is the supervisor's responsibility to present the consequences of the undesirable behavior, and to identify and get agreement on suitable alternatives. This is a basic strategy to bring marginal performance to an acceptable level and to help employees gain experience that will generate better alternatives.

Research shows that employees enjoy work that allows them to accomplish something worthwhile. Thus, the structure of the work itself can motivate performance. Each job should include the conditions for success as outlined in this section.

- Clearly communicated procedures
- Clearly defined desired results
- Adequate training and time to develop skill
- Resources
- Feedback

Jobs should be expanded where possible to allow

- An understanding of the value for the customer
- A team environment where the job can be seen as contributing to a common goal

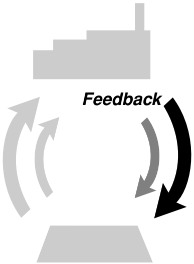
Employees strive for achievement and recognition. This is one conclusion of the research done by Fredrick Herzberg in the 1950s [5]. To motivate positive behaviors, the supervisor in a performance management role needs to be present and provide recognition for things done right (and better than before). The recognition needs to be sincere and specific, describing the behavior or accomplishment.

For example, instead of simply saying a general "Good job, Joe" in passing, a supervisor should give specific feedback about the desirable behavior being recognized. The supervisor might say, "Good job, Joe. Thanks for letting Frank know about the rattling noise and the shavings you noticed from the braiding machine. Frank said he got right to the source—loose bolt on the feeder arm—and fixed it last night. That probably prevented a breakdown on today's shift." Or better yet, the supervisor could give the recognition at the morning meeting in front of the whole crew. This further esteems Joe and allows everyone to learn from the situation.

FEEDBACK: MAKING REALITY VISIBLE

Feedback is information about the work being done, given to those doing the work, for the purpose of control and improvement (Fig. 2.4.5). As human beings, we process feedback naturally. When driving a car, we take information from gauges, road conditions, traffic signals, and so on, and automatically make adjustments to control the car and steer toward our destination. Feedback makes it possible for us to get to work on time, without getting lost, having an accident, or getting a speeding ticket. In the workplace, feedback provides information that helps us control the work we do and steer toward desired results. Based on feedback, employees may recognize a need to stay focused on what is important, speed up, slow down, be more cautious, double-check a method, inspect more closely, get help, make an equipment adjustment, or solve a problem.

Feedback brings information about important elements of work to the attention of those doing the work. It makes the reality of those elements visible. In order for feedback to be



Feedback is information about work provided to those doing the work for the purpose of control and improvement.

FIGURE 2.4.5 Feedback.

effective, it needs to be designed with the end purpose in mind. What will the information be used for, and how will it help the recipient achieve the desired results? Feedback comes in many forms, but basically can be used to

- Measure progress toward a goal
- Monitor the conformance of a process to standards
- Facilitate an individual learning a new method or improving a skill
- Summarize the effectiveness of a work group

Measure Progress Toward a Goal

This type of feedback helps employees gauge how they are doing against a predefined measure of success. The goal can be short-term like a production quota for a shift, or long-term such as a customer satisfaction rating. Establishing a goal helps workers focus on what needs to be attained. It serves to motivate the performance that will lead to achieving the goal. The goal needs to be realistic, easily understood, and precisely defined. The measure should be easily obtained and displayed so that every individual affected can monitor progress toward the goal.

For example, an appropriate goal for a work cell is a production goal of 100 units (no more, no less) of Model 67 on this shift to fill customer orders. Progress is tracked on a posting board visible to everyone. As each unit is completed, the final operator in the cell increments the total for the hour and the cumulative total produced on the shift. In this example, the goal is clear, the feedback is easily understood and not costly to obtain, and the progress toward total and incremental goals is visible to all. This type of feedback helps employees gauge how they are doing against a predefined measure of success.

In any work group, goals should measure what is important to the success of the group. Defining the objectives of the group is the first step toward selecting measures. It's likely that any group will need several goals to represent the factors important to success. Carl G. Thor calls this type of group a *family of measures* in his article, "The Family of Measures Method for Improving Organizational Performance" [6]. Using a group or family of measures allows for weighing and balancing the importance of each factor that contributes toward accomplishing overall desired results. Some possible measures include

- *Productivity*—cost (inputs) per output
- *Quality*—absence of defects, minimum of waste in processes, delivery of a valuable product or service to the customer
- *Timeliness*—on-time delivery
- *Cycle time*—time from start to finish for a key process

- *Utilization*—resources used versus resources available
- *Safety*—maintenance of safe conditions, absence of accidents and incidents
- *Employee skill development*—progress toward acquiring needed skills
- *Housekeeping*—progress toward or maintenance of a clutter-free, organized, and clean workplace
- *Customer focus and satisfaction*—knowledge of requirements and success meeting them
- *Creativity and innovation*—"out-of-the-box" thinking with tangible results
- *Outcome*—ultimate outcome of effort like profit, market share, and so on

Monitor the Conformance of a Process to Standards

This type of feedback comes in many forms, but the purpose is to monitor process parameters and identify any deviation in order to correct it before it becomes a problem. Process feedback is critical to performance management because it allows intervention at the point of detection to correct and prevent continued occurrence.

Types of Process Feedback

- Electronic devices can provide feedback on variables such as speed, temperature, and pressure. A programmable logic controller (PLC) can stop a process and display a signal when a problem is detected, or simply display an alarm to alert an operator of deviation in an operating parameter so that action can be taken.
- In a production situation, mistake-proofing (poka-yoke) devices provide process feedback. These devices are designed to detect errors and let the operator know immediately there is a problem. For example, when materials do not conform to the shape of a fixture, or when a finished part is missing a groove and does not go through a profile device, the operator is immediately aware of the problem. In a flow manufacturing operation, incoming and outgoing inspections serve a similar purpose. When an operator inspects an incoming part and finds a defect, the operator communicates with the upstream process so immediate action can be taken.
- Visual storage strategies provide feedback that simplifies finding items and encourages proper replacement. On a tool cart where each item has an exact location marked by the tool's outline, it only takes a glance to tell if everything is in its place. The outlines also serve as a visual reminder to the individual using the tool that it is necessary to return it to the proper location after use.
- Visual production control methods provide feedback on the flow of a process. If parts begin piling up at one station, or another station is lacking the necessary parts, the message is clear—something is "out of sync."
- Cleaning and inspection, as used in a 5-S program or a total productive maintenance (TPM) system, serves as a means of getting feedback on equipment conditions. Employees are trained to understand the inner-workings of their equipment in order to clean and inspect periodically and look for things that indicate wear or nonconforming conditions like leaks, shavings, and loose bolts. The goal is to correct the deteriorated condition before it leads to an equipment breakdown or a quality problem.

Facilitate an Individual Learning a New Method or Improving a Skill

Feedback specific to an individual can come from work itself, from a supervisor who is observing, or from manually or electronically collected data. The purpose is to give information on performance that can be used to develop the individual's skill and confidence in performing the work. Similar to learning a golf swing, the learner needs frequent practice, feedback, and coaching to master the skill. A mistake-proofing device or employee cross-checking can provide real-time feedback on the work. Intermediate goals for production can also be set and monitored with simple targets, such as a bin with marked graduations as targets for hourly production volume.

In learning situations, the supervisor or another employee can be involved to review the work and provide feedback on method and pace. This coach can use performance measurement techniques, such as production or cycle counting to measure an employee's performance versus the standard, or performance rating to evaluate skill and effort. Performance data that are collected electronically or manually can also be used to track an employee's progress. For example, cashiering data from the front register in a retail store can give information such as time per scan that can be measured.

Summarize the Effectiveness of a Work Group

Management control reports provide information about what happened in an operation over a specific period of time—daily, weekly, or monthly. The purpose is to review and evaluate workers or work groups on measures such as performance, utilization, and productivity. Performance reports are usually one output of a larger system that may be designed to provide data for payroll, costing, accounting, or planning as well as for performance. Typically these reports represent a summary of production data collected in the production unit including the product(s) produced, quantity completed, productive hours for each individual, delay time, and total hours worked. In addition, the reports include calculated indices such as

- *% utilization*—indicates the percentage of productive hours in relation to total work time.

$$\%\ \text{Utilization} = \frac{\text{Total Hours Worked} - \text{Delay Hours}}{\text{Total Hours Worked}} \times 100$$

- *Earned standard hours*—the number of hours the standard allows for the quantity of parts completed. Essentially it is the "should have taken" time for the quantity produced.

$$\text{Earned Standard Hours} = \text{Standard Hours per Piece} \times \text{Pieces Produced}$$

- *% performance*—indicates the relationship of the actual time used to perform a task to the time the task should have taken (earned standard hours) based on standards. It is a measure of how much of a goal or standard (quantity and time) is achieved, or how well a worker's (or group's) actual work time compares to the standard time.

$$\%\ \text{Performance} = \frac{\text{Standard Hours Produced}}{\text{Actual Hours Worked on Standards}} \times 100$$

- *Productivity*—indicates the ratio of actual production to the standard production goal. A measure of the overall effectiveness of both management and labor.

$$\%\ \text{Productivity} = \frac{\text{Standard Hours Produced}}{\text{Total Paid Hours}} \times 100$$

- *Efficiency*—represents the ratio of actual output to standard output.

$$\%\ \text{Efficiency} = \frac{\text{Actual Output}}{\text{Standard Output}} \times 100$$

- *Cost per standard hour*—represents the actual labor cost ($) per standard hour produced.

$$\text{Cost per Standard Hour} = \frac{\text{Actual Hours Worked} \times \text{Labor Rate}}{\text{Earned Standard Hours}}$$

The value of this type of feedback lies in the ability to reflect on the effectiveness of the work group for the day or week, identify trends and improvement opportunities, or make comparisons to other operations. When used in conjunction with real-time measures in the workplace, a supervisor can intervene to make corrections that prevent problems and reflect on overall group effectiveness.

Feedback makes reality visible. With feedback we know how well we are doing in areas that are important. We know our progress toward goals, the functioning of our processes, the development of skills, and the results of our overall effort.

In order for feedback to be effective, it needs to measure things that are important, controllable, and open to improvement. The measure needs to be understandable and to motivate actions that contribute to the desired result.

ACTION: TAKING ACTION TO IMPROVE

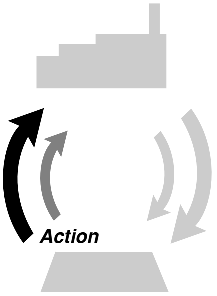
Recognize Feedback and Take Corrective Action

Supervisors and employees need to make decisions and take action based on feedback from the workplace (Fig. 2.4.6). For simple feedback that is part of the normal work process, employees should be trained to make routine decisions within the bounds of their skill level. Employees can make process and equipment adjustments and follow a troubleshooting procedure. They should know how to document incidents and get help when they need it. For feedback that indicates an unusual situation, supervisors and employees need to be able to analyze the situation to determine the root cause of the problem, then take action to correct and prevent future occurrences. A supervisor should initiate the process and coach employees to take initiative as well.

The following is an example of how a supervisor can use the performance management approach, recognizing feedback and taking action:

> After a model change, the supervisor sees an experienced worker at the end of a work cell, standing idle with an empty kanban (no work). A less-experienced operator upstream is puzzling over materials that just do not seem to fit perfectly into the machine die. The supervisor, acting as a coach, invites the experienced operator to help with the problem. The experienced operator asks, "Did you check the die number?" The inexperienced operator answers, "No," but checks, and it is the right die. "Is the die out of alignment?" The experienced operator and supervisor recognize the misalignment and explain how to detect it. The experienced operator shares a tip that can be used to monitor and correct the die alignment. The operator is back on line in minutes. Total downtime 2 minutes. No wasted material, no defective product.

The supervisor, using the performance management approach, is in the workplace looking for feedback on progress toward goals, process conformance, and skill development. When a



It is the supervisor's job to enable workers to respond to feedback with appropriate action.

- Progress toward goals
- Recognize
- Correct
- Analyze
- Improve

FIGURE 2.4.6 Action.

PERFORMANCE MANAGEMENT: A KEY ROLE FOR SUPERVISORS AND TEAM LEADERS

problem is identified, the supervisor engages employees in the problem-solving process, encouraging them to get involved and share knowledge. The result? As in our example above, downtime is reduced, and waste is minimized. The experienced operator is empowered to get involved and help where needed. The inexperienced operator learns new operating and troubleshooting procedures. The supervisor captures ideas for improved methods that can be shared with other operators and incorporated into the standards and training materials. In this situation, because the supervisor was available, she could coach employees to be more self-sufficient in pursuing the desired results.

Analyze and Improve

A supervisor needs to be perceptive of feedback from many sources to evaluate the success of the workers and the work group, and to provide help when needed. When things are going well, the supervisor should recognize the employee's achievement. When there is a performance problem, the supervisor needs to get involved as needed and facilitate a resolution. Using the performance management model as a guide (Fig. 2.4.7), the supervisor can analyze a situation to determine what factors might be missing. A systematic review of the conditions for success will help the supervisor determine what may be influencing the nonperformance and provide direction for a solution.

- *Communication*—Has there been a miscommunication or a misunderstanding?
- *Skills*—Have adequate training and practice been provided?
- *Resources*—Are the necessary resources available?
- *Feedback*—Is there feedback given to keep performance on track?

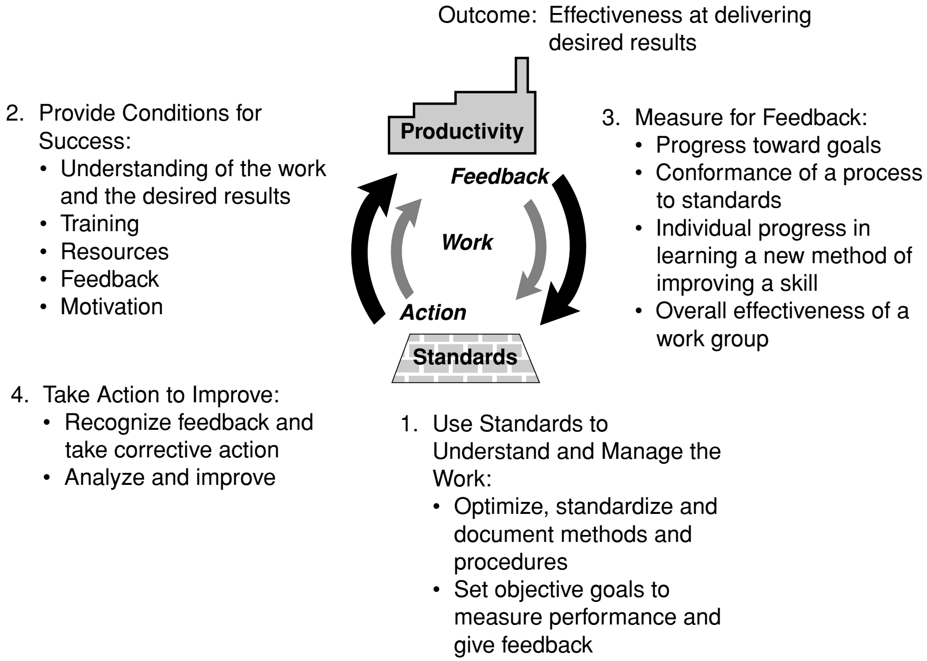

Outcome: Effectiveness at delivering desired results
2. Provide Conditions for Success:
• Understanding of the work and the desired results
• Training
• Resources
• Feedback
• Motivation
Productivity
Feedback
Work
Action
Standards
3. Measure for Feedback:
• Progress toward goals
• Conformance of a process to standards
• Individual progress in learning a new method of improving a skill
• Overall effectiveness of a work group
4. Take Action to Improve:
• Recognize feedback and take corrective action
• Analyze and improve
1. Use Standards to Understand and Manage the Work:
• Optimize, standardize and document methods and procedures
• Set objective goals to measure performance and give feedback

FIGURE 2.4.7 Maynard performance management approach summary.

- *Motivation*—Does the employee recognize the consequences of not performing? Is the employee aware of the alternative choices for behavior? Are there negative consequences for performing the desired behavior? Are there positive consequences for *not* performing the desired behavior?

The supervisor needs to involve the employees in recognizing the problem and defining a solution. Then, the supervisor needs to follow up to see if the solution works and recognize employee effort.

IMPLEMENTING PERFORMANCE MANAGEMENT

Overview

To implement a performance management approach in an organization there must be a commitment from upper management to

1. Understand the work of the supervisor and clearly communicate the expected results.
2. Provide the supervisor with necessary conditions for success.
   - The time and freedom to be closely involved with the work and the workers in the workplace.
   - Up-to-date engineered time standards for use in planning and giving feedback on performance.
   - Training in the performance management approach.
   - Consistent and specific feedback.
   - Specific and sincere recognition.
3. Establish ways to give feedback on performance. The supervisor will recognize what management values by what is measured and enforced. Supervisors need feedback on
   - Progress toward goals
   - Successful application of the performance management approach
   - Progress in learning new skills
   - Effectiveness of their work group's efforts

   Management control reports can be used to measure group performance. To improve the value of the report and to foster cross-department communication and learning, supervisors should meet regularly and report on the issues impacting their group's performance. This encourages supervisors to study the report, identify factors that influenced the results, and learn from each other's experience.
4. Take action to help the supervisor improve. Provide training in the performance management approach, including work measurement techniques, visual communication techniques, interpersonal communication, problem solving, training methodology, measurement for feedback, and coaching for improved performance. Provide in-the-workplace coaching on specific job performance issues that are important to success.
5. Acknowledge accomplishments.

CONCLUSION

The Maynard performance management model described in this chapter provides a framework and a complete set of tools for a supervisor or team leader to use in managing employee performance in the workplace. Using this approach, one can influence the performance of individuals and work groups on the job to achieve the desired results. In addition, the model can be used by managers to evaluate and identify gaps in their organization's performance management approach.

ACKNOWLEDGMENTS

The following individuals were instrumental in the conception and development of the Maynard performance management approach: Roger Weiss, president; Kjell Zandin, senior vice president; Nick Davic, senior consultant; and John Minnich, business development manager of H. B. Maynard and Co., Inc., and Lee Ann Robatisin, former production supervisor of H. J. Heinz Co., Inc.

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FURTHER READING

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BIOGRAPHY

Mary Ann Broderick is an instructional designer and information developer for H. B. Maynard and Co., Inc. in Pittsburgh, Pennsylvania. Her career spans 17 years in business and industry, working closely with supervisors and managers in production operations. She holds a master's degree in public management from Carnegie Mellon University.

CHAPTER 2.5

MANAGING CHANGE THROUGH TEAMS

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Continuous change is a major force with which contemporary managers must deal. The management of change is accomplished through the development and process for the strategic management of the enterprise—that is, the management of the enterprise as if its future mattered.

Enterprise change can be managed through the use of project management philosophies and processes to include the use of nontraditional teams to function as a focal point for both operational and strategic change in the enterprise. Some of the principal teams include those that provide for the management of reengineering, benchmarking, self-managed production strategies, and concurrent engineering for the simultaneous development of products, services, and organizational processes.

The results from the use of nontraditional teams in the management of the enterprise include reduced costs, enhanced productivity, earlier commercialization, and better use of enterprise resources. As an organization uses these teams, changes in the culture, alternative career paths, and general improvement in the use of resources are realized. Such changes help the enterprise become more competitive in the global marketplace.

Change is a constant companion in contemporary organizations. Social, political, economic, legal, technological, and competitive variations impact all organizations today. Although the practice of project management has been with us for centuries, the literature that expresses the theoretical foundations of project management has evolved only in the last few decades. As project management has gained maturity as a theory and practice for managing interfunctional and interorganizational activities, its application has spread to many nontraditional uses, becoming a key means by which operational and strategic initiatives are managed in contemporary times. Project management has laid down the strategic pathway for the management of product, service, and process change by present-day enterprises. The growing success in the use of project management has given impetus to the further use of teams to carry out benchmarking, reengineering, and concurrent engineering initiatives, as well as the use of self-managed production teams to improve manufacturing efficiency and effectiveness.

In this chapter, the use of alternative teams will be explored and described as powerful organizational designs to deal with the inevitable changes that face all organizations today. Members of the industrial engineering community have a vested interest in understanding and accepting the use of teams in dealing with change. The educational background and experience of industrial engineers usually reflect career paths that have been exposed to some aspect in the technical and managerial considerations of change.

THE NATURE OF TEAMS

Alternative teams are becoming more commonplace in contemporary organizations. The use of teams continues to modify the theory and practice of management. *Business Week* magazine [1] has stated that "the formation and use of teams is an art form for corporate America." For the industrial engineering professional, the ability to serve as a contributing member and to provide leadership while serving on such teams has become a core competency relative to their careers in today's enterprises. Never have there been greater opportunities for industrial engineers to gain experience in the management of interfunctional and interorganizational activities. Survival and growth are the motivating forces that condition everyone's behavior in today's organizations. Workers, professionals, and executives at all levels of the enterprise must gain the knowledge, skills, and attitudes needed to work with teams that deal with operational and strategic change, particularly in maintaining competitive competency in the global marketplace. According to *Business Week,* those companies that learn the secrets of creating teams are winning the battle for global market share and profits. Those that don't are losing out. In the material that follows, a description of these teams is given.

TRADITIONAL PROJECT TEAMS

Traditional project teams have emerged over several decades, with their use established by custom influenced primarily from the construction and defense industries. Project teams can be described as having the following characteristics:

1. They involve the design, development, and production (construction) of physical entities, which contribute to the capabilities of customers. A new highway, a hydroelectric power–generating dam, a new weapon system, or a new manufacturing plant are examples of the results of such teams.
2. A distinct life cycle is found in these projects, starting with the conceptualization of an idea and progressing through the design, development, production (construction), and eventual transfer to serve the customer's purposes.
3. Substantial financial, human, and other resources are assembled and used by the time the project results have been attained.
4. The results that the project teams produce become building blocks in the design and execution of both operational and strategic initiatives for the enterprise.
5. A substantial body of knowledge exists concerning the theory and practice of these project teams.
6. A growing number of professional associations have emerged in the recent past, such as the Project Management Institute (PMI), which at the time of writing this chapter has over 65,000 members drawn from the international community.

ALTERNATIVE TEAMS

Additional teams have come forth to deal with interfunctional and interorganizational opportunities and problems in contemporary organizations:

- *Reengineering teams* provide an organizational focus to bring about a fundamental rethinking and radical redesign of business processes to achieve extraordinary improvements in organizational performance such as cost reduction, quality improvement, improved services, and earlier commercialization of projects and services. Today, much attention is given to the use of reengineering teams as a means for improving performance. However, a note of caution: Michael Hammer, the guru of reengineering strategies, openly admitted that in 1993, 70 percent of the reengineering efforts failed [2]. Nevertheless, reengineering teams are growing in use, as are other organizational strategies for improving organizational performance.

- *Production/process development teams,* often called concurrent engineering, or simultaneous engineering teams, provide the means for the parallel design and development of products, services, and processes (manufacturing, marketing, purchasing, after-sales services, engineering, and so on) that usually result in products and/or services of higher quality with lower costs, as well as earlier commercialization.
- *Benchmarking teams* measure organizational products, services, and processes against the most formidable competitors and industry leaders, usually resulting in improved performance strategies for the enterprise.
- *Self-managed production teams* are generally small, independent, self-organized, and self-controlling organizational units in which members plan, organize, determine, and manage their duties and actions with little traditional supervision. These teams make decisions in such areas as task assignments, work schedules, work design, training, equipment usage and maintenance, problem solving, member counseling and discipline, hiring and firing of team members, and sometimes having authority to carry out merit evaluations, promotions, and pay raises. These teams are found in traditional manufacturing environments as well as in other production activities beyond manufacturing where the term production is used in the sense of creating utility—the making of goods and services for customer needs. Industrial engineers working in the manufacturing environment should find ample opportunity to work with and provide technical and managerial guidance to these teams.
- *Crisis management teams* are hopefully not ever needed but nevertheless should be appointed and developed to deal with any crisis that may arise in the enterprise's activities. Natural disasters, loss of key personnel, loss of plant and equipment, accidents, product liability suits, and such misfortunes are all potential crises that can impact the well-being of the enterprise. In a few moments, a stable situation in an enterprise can deteriorate, leaving the organization fighting for its life. How well an enterprise responds to crises will be dependent on the timeliness and thoroughness of its planning. How well a crisis management team responds in a damage control mode and deals with the stress, public relations, decision making, and other extraordinary strategies to contain the disaster will often determine how well the organization is able to survive a crisis.
- *Quality teams* and their use have gained considerable acceptance in today's organizations. Such teams, properly used, can facilitate total quality improvements in products, services, and organizational processes as well as bring about productivity improvements, improvement of labor-management communication, and enhance job satisfaction and the quality of worklife for employees. Much has been written about total quality improvement in current books and periodicals. The use of quality teams is only one part of total quality management (TQM). Such teams are an important part of TQM and join strongly with the growing use of teams as organizational designs to cope with change in the enterprise.
- *Task forces* are a form of teams that are ad hoc groups used to solve short-term organizational problems or exploit opportunities for the enterprise. A task force is quite similar to a nontraditional project team, and its use can help the enterprise deal with change. The use of task forces as organizational design units appeared early in the management literature. Today, an enterprise may organize task forces to deal with ad hoc problems or opportunities. For example, a major food processor appointed several organizational units called task forces to conduct ad hoc studies and recommend strategies to senior management for improving performance of the company. These task forces evaluated such diverse activities as (1) purchasing strategies, (2) reduction of overhead costs, (3) corporate downsizing and restructuring, (4) improvement of manufacturing strategies to reduce production costs, and (5) developing strategies for improving the quality of work life for employees.

- *Product management teams* are generally considered an early form of project management. As the marketing of goods and services became more complex, senior managers chose to use organizational designs that were adaptive and could concentrate on marketing single and multiproduct lines. Marketing specific product lines and satisfying specific groups of consumers while remaining competitive demanded organizational designs that could facilitate the focus of resources to accomplish product marketing objectives. The origins of product management can be traced back to the Procter & Gamble Company in 1927. A new product, Camay soap, was not meeting sales projections. One individual was assigned as a product manager to provide a focus for marketing the soap. This early product manager worked across organizational boundaries to improve marketing of Camay soap. The idea of a product manager, augmented with team members, caught on in other companies such as Colgate-Palmolive, Kimberly-Clark, American Home Products, and Johnson and Johnson. In some companies, the product management team is called a brand management team. These product management teams worked across organizational boundaries and created an early form of the matrix organization.

THE NATURE OF ALTERNATIVE TEAMS

The alternative teams that have been described above have many of the characteristics of traditional teams. Yet these teams have a life of their own and have the following characteristics:

1. The teams are usually created to improve the efficiency and effectiveness of the organization through strategies that work across functional and organizational boundaries.
2. Much of the teams' work is directed to improve the manner in which product, service, and organizational processes are changed and improved.
3. Such teams require an early conceptualization of the problem or opportunity with which the team is going to deal, and the work of the team begins immediately through becoming immersed in the existing problems and opportunities for which the team was appointed.
4. Although there may be hardware considerations involved, these teams typically work on the improvement of the manner in which resources are created and utilized in the enterprise.
5. The "deliverables" of the efforts of these alternative teams can take the form of reports, recommended actions, plans, studies, strategies, new or improved processes, policies, procedures, or general schemes for a better use of enterprise resources.
6. The management of these teams is patterned after the theory and practice laid down by project management.
7. The results produced by these teams have important linkages with the operational and strategic initiatives of the enterprise.
8. The cultural ambience of the enterprise is influenced by these teams, particularly in terms of the patterns of authority and responsibility that come forth in the performance of individual and collective roles in the enterprise.

THE CONTRIBUTION OF ALTERNATIVE TEAMS

The contributions made by these teams can extend throughout the enterprise and its environment. These contributions usually center on the following important initiatives of the enterprise:

Market needs assessment
Competitive analysis

MANAGING CHANGE THROUGH TEAMS

Assessment of organizational strengths and weaknesses
Benchmarking
Establishing strategic performance standards
Vision quest
Market research
Product–service–process development
Business process reengineering
Crisis management
Self-managed production initiatives
Resolution of short-term considerations
Quality improvement
Audit processes
New business development teams

The value of using teams in the management of the enterprise is noted in an article that appeared in *Fortune* magazine, which stated in part, "The ability to organize employees in the innovative and flexible ways and the enthusiasm with which so many American companies have deployed self-managing teams is why U.S. industry is looking so competitive" [3]. The work and impact that these teams have facilitated is described in the following [4]:

Market Needs Assessment

One company used "headlight teams" to evaluate a preliminary set of industry discontinuities or drivers that had been developed by senior management that were likely to affect the company. The teams evaluated each discontinuity in depth, seeking to discover how the trend might impact current customers and current economics in the company. In addition, the teams evaluated the dynamics of the trends and the probable factors that might accelerate or decelerate these trends. Finally, a summary of which companies were likely to gain or lose from these trends was provided. As the assessment by the teams began to emerge, other teams in the company composed of business unit managers and corporate managers reviewed the strategic importance the trends might have for the company. After the teams had completed their work, a penetrating insight into industry changes likely to impact the company was done [5].

Competitive Assessment

No enterprise can exist without being aware of its competitors. In the global marketplace, companies watch each other closely to determine what new or improved products and services are developing. From this, a company can determine whether to add to their inventory of products and services in the marketplace. A major company in the aerospace industry uses competitive assessment teams to do an explicit assessment of its competitors whenever the company elects to form a proposal team and compete on a proposal to the Department of Defense for a new military system. These competitive assessment teams have the objective of finding out as much as possible about the strategy likely to be used by competitors who are expected to bid on the proposal for the new system. The teams establish what needs to be known about the competitors' strategies, their strengths and weaknesses, and the probable bid strategies they are likely to pursue, ranging from their technical proposal, cost considerations, pricing and bid strategy, and any likely distinct edge that the competitors might have.

Organizational Strengths and Weaknesses

Concurrent with the development of an assessment of an enterprise's competitors, an evaluation needs to be done through the medium of an interdisciplinary team of the company's strengths and weaknesses vis-a-vis its most probable five or six competitors. A toy manufacturer has a sophisticated process for determining what its competitors are likely to do in designing and bringing out innovations in the toy business. Once a clear strategy of a competitor's product development effort has been determined, then a team drawn from the different disciplines of the company is appointed to evaluate what the competitor's product might do in the marketplace, and how well the company is able to meet the competitor in that marketplace. An explicit analysis of the company's strengths and weaknesses is carried out, and then passed on to the key decision makers in the company who are charged with the responsibility for developing a remedial product strategy to counter what the competitors are doing.

Benchmarking

The results of benchmarking, once determined, can help in the decision making about what should be changed in the enterprise. In addition, benchmarking results provide a standard against which organizational performance can be judged. Benchmarking is usually used in three different contexts: (1) competitive benchmarking of the five or six most formidable competitors; (2) best-in-the-industry benchmarking where the practices of the best performers in selected industries are studied and evaluated; and (3) generic benchmarking in which business strategies and processes are studied that are not necessarily appropriate for just one industry. A couple of benchmarking examples follow.

1. At General Motors, benchmarking is becoming a major strategy in the company's drive to improve its products, services, and organizational processes. Every new operation must be benchmarked against the best in the class—to include looking beyond the car manufacturing industry. General Motors has a core group of about 10 people whose responsibilities are to coordinate its worldwide benchmarking activities [6].
2. Union Carbide's Robert Kennedy used benchmarking to find successful businesses, determine what made them successful, and then translate their successful strategy to his company. The benchmarking team at Union Carbide looked to L.L. Bean to learn how it runs a global customer service operation out of one center in Maine. By copying L.L. Bean, Union Carbide teams were able to consolidate seven regional customer service offices, which handled shipping orders for solvents and coatings, into one center in Houston, Texas. By giving employees more responsibility and permitting them to redesign their work, 30 percent fewer employees were able to do the same work—including the analysis of processes to reduce paperwork to less than half. For lessons on global distribution, Union Carbide looked to Federal Express, and for tracking inventory via computer, Union Carbide borrowed from retailers such as Wal-Mart [7].

Benchmarking makes sense as a means of gaining insight into how the enterprise compares to its competitors and the best in its industry. Once the comparison has been carried out, then performance standards for the enterprise can be established.

Establishment of Strategic Performance Standards

The strategic performance standards for an enterprise are reflected in statements of its mission, objectives, goals, and strategies. Let us discuss these in more detail.

Mission. An organizational mission is the final performance standard for the enterprise. Such a mission is the "business" that the enterprise pursues. All organizational activity must be judged according to how such activity ultimately contributes to the mission. As a declaration of the broad, enduring intent that an organization seeks to fulfill, final performance of the enterprise must be judged by how well its organizational mission is attained. As an example, a drug manufacturer declares its mission to be "the development, manufacture, marketing, selling, and distribution of a broad line of high quality generic drug products at competitive prices."

Objectives. Organizational objectives are ongoing, enduring end purposes that must be achieved in the long term to ensure accomplishment of the mission. These objectives can be stated in quantitative or qualitative terms. For example, a computer company defines one of its objectives as "leading the state-of-the-art of technology in its product lines." Another company defines one of its objectives as "meeting or exceeding the state-of-the-art of competitors in machining capability."

Goals. A goal is a milestone whose specificity can be measured (on time–based points) that the enterprise strives to meet as it pursues its objectives. When properly selected and attained, goals provide specific insight into how well the strategic management system is preparing the enterprise for its future. One company stated one of its goals as follows: "We intend by the end of 1984 to complete the transition begun in 1983 from a predominantly R&D service company to an industrial manufacturer."

Strategies. A strategy determines the means for how resources will be used to accomplish organizational mission, objectives, and goals. Such means include action plans, policies, procedures, resource allocation schemas, organizational designs, motivational techniques, leadership processes, monitoring, evaluation and operation of control systems, and the use of project teams as building blocks in the design and execution of strategies. Many descriptions are entailed in delineating strategies. For example: "Develop a culture that emphasizes quality improvement, cross-functional training, and understanding the needs of customers as the keys to success in this highly competitive market." Strategies also include those policies that guide the thinking of the decision makers in the enterprise. "Thou shalt not kill a new product idea" is a well-known policy of the 3M company, a policy that has helped facilitate the flow of new product and service ideas from people in the company—from senior managers to workers in the factories.

Contemporary enterprise managers faced with growing, unforgiving competition in the marketplace use teams to identify and study the alternative performance standards available and make recommendations concerning which are the most promising alternatives for the enterprise to pursue. By reviewing the results of the work of other teams, such as benchmarking and competitive analysis teams, they have a better chance of finding and selecting those strategic alternatives that best fit the enterprise's strengths and weaknesses.

Vision Quest

Because of the elusive nature of finding a vision for an organization, teams with proven track records in creativity (i.e., leading to innovative products, services, and organizational processes) can be used to do the analysis and brainstorming usually required to see and bring a meaningful vision into play. For example, an aircraft manufacturer appointed an interdisciplinary team to examine the potential for the expansion of the company's after-sales service business. The company's superior after-sales support was a major reason for customers to purchase aircraft from the manufacturer. After deliberating for several months, the team developed a market plan which included a vision for the expansion of the company's after-sales service capabilities. Supported by this vision, the company developed strategies for superior after-sales service, which would consistently outperform what competitors are able to do.

Market Research

A major food processor appointed a team to evaluate the global potential for its line of prepared foods. Over a one-year period the team traveled extensively to assess local country markets, talk with subsidiary managers in the countries visited, and in general, collect information concerning the eating and purchasing habits of people in both developed countries and in those countries that were undergoing social and economic development. Several major findings came out of this work:

1. The demand for processed convenience foods will remain strong in the developed countries and spread to those developing countries where discernible increases in the living standard of the citizenry are evident. As the income level rises in the developing countries, new markets will open to include sales for pets as well as humans.
2. Major markets that are expected to continue and in some situations to accelerate include prepared-food supplies to food service organizations, infant foods, and dietary and weight control foods.
3. The social and economic changes that have occurred throughout the world will likely not be without social and military upheavals in certain areas of the world.
4. Technological innovation in the growing of crops and the manufacture and processing of food products will continue, giving a strategic advantage to those enterprises that are able to keep up with or lead technological improvements in food processing initiatives.

Product–Service–Process Development

By using concurrent engineering teams to simultaneously develop products, services, and processes, significant benefits can be realized such as

- Reduction of engineering change orders of up to 50 percent
- Reduction of product development time between 40 and 50 percent
- Significant scrap and rework reduction by as much as 75 percent
- Manufacturing cost reduction between 20 and 40 percent
- Higher quality and lower design costs
- Fewer design errors
- Reduction and even elimination of the need for formal design reviews since the product–process development team provides for an ongoing design review
- Enhanced communication between designers, managers, and professionals in the supporting processes
- Simplification of design, which reduces the number of parts to be manufactured, creates simplicity in fixturing requirements, and allows for ease of assembly
- Reduction in the number of surprises during the design and manufacturing processes
- Greater employee involvement on the concurrent engineering teams leading to enhanced development of their knowledge, skills, and attitudes

As an example, at the Boeing company, customer service has become a key competitive factor. The company maintains field representatives in over 56 countries, which provide training, engineering, and spare parts to about 500 airlines around the world. Their superior after-sales support is a major factor in the company's continued market leadership in commercial aircraft. In developing the newest member of the Boeing jetliner family, the 777, the company worked with its customers more closely than ever before to develop, design, and produce a product that provides superior value to the customers. By bringing key stakeholders together—like customers, suppliers, and the Boeing project team, which was composed from the disciplines of engineering, manufacturing, marketing, after-sales support, and so forth—information was shared to facilitate a more efficient process for producing a new aircraft. The use of integrated product teams (concurrent engineering teams) at Boeing eliminated the artificial barriers between organizations and functions and provides a more efficient cost-effective process for the development of new products and services [8].

Business Process Reengineering

The focus of reengineering is to set aside the current ways of working and painstakingly examine the processes involved in doing the work, to discover new, innovative, and breakthrough ways of improving both operational and strategic work in the enterprise.

There are benefits and limitations to what reengineering can do for the enterprise. For example, during one of the largest process reengineering projects ever undertaken, GTE telephone operations management was stunned to find out that the administrative bureaucracy of the company was reducing productivity by as much as 50 percent. As part of its reengineering effort, GTE examined its own processes and benchmarked 80 companies in a wide variety of industries. Reengineering teams then created new concepts, approaches, policies, and procedures for the new processes. To provide incentive to the benchmarking teams, specific goals were set: (1) double revenues while cutting costs in half, (2) cut cycle time in half, (3) cut product rollout time by three quarters, and (4) cut systems development time in half. The company's reengineering efforts helped to integrate everything it learned into a customer value-added path.

One key result of the reengineering effort at GTE was the promotion of a cultural change, a change that promoted a sharing among employees so they would be open to any and all possibilities for improving the way they work.

As a result of a reengineering initiative, a drug company moved from a functionally organized company into a focused, project team organizational design. The new organizational design was charged with the responsibility of acting as a focal point to conceptualize and bring drugs to market as soon as possible. The processes for bringing drugs to the market were altered, the culture of the enterprise was changed from a "command and control," hierarchical, top-down bureaucracy to a cross-functional, matrix organization.

Crisis Management

Recent history has shown that the costs to an enterprise of a crisis can be staggering. Government policy requires that the owners of plants and facilities that use hazardous material have an emergency plan in place to include how a damage control team is organized and trained in advance on how to respond to a crisis. The outside forces, such as the media and others that appear when a crisis occurs, dictate that the organization be prepared to respond. A timely and calculated response has the real promise of limiting the range of legal and stakeholder relations and liabilities, and consequently minimizes the damage done by an emergency. A crisis, such as an oil spill, will have legal, media, and political stakeholders involved in a matter of hours. The enterprise has to be prepared to respond to environmental, legal, media, political questions, and so forth, in a minimum of time. It is absolutely necessary to be prepared in advance as much as possible for such responses. Two recent airline disasters, TWA Flight 800, and U.S. Airways Flight 427 that crashed in Pittsburgh on September 8, 1994, resulted in the formation of crisis management teams. The work of these teams continues, particularly in trying to determine the cause of these crashes.

Self-Managed Production Initiatives

A self-managed production team (SMPT) is generally a small, independent, self-organized, and self-controlling group of people in which the members carry out the management functions of planning, organizing, motivating, leading, and controlling themselves. SMPTs perform a wide variety of management and administrative duties in their area of work, including

- Designing jobs and work methods
- Planing the work to be done and making job assignments
- Controlling material and inventory
- Procuring their own supplies
- Determining the personnel required
- Scheduling team member vacations
- Providing backup for absentees
- Setting goals and priorities
- Dealing with customers and suppliers
- Developing budgets
- Participating in fund planning
- Keeping team records
- Measuring individual and team performance
- Maintaining health and safety requirements
- Establishing and monitoring quality standards and measures
- Improving communications
- Selecting, training, evaluating, and releasing team members [9]

A couple of examples of SMPTs follow:

- In one factory, the manufacturing workers manage themselves. There is a deep belief by the workers at this factory that constant change is the only constant. At this factory, the work is technical and teachable. What isn't teachable is initiative, curiosity, and collegiality. Accordingly, during the hiring process every attempt is made to weed out loners and curmudgeons. People start as contractors and become employees only after proving they're self-starters and team players. The teams select their own leaders who maintain oversight of the team's activities to include quality, training, scheduling, and communication with other teams. Management establishes the mission for the plant, but the workers are expected to design and implement strategies for fulfilling that mission. The professionals have cubicles next to the assembly cells. Every procedure is written down, but workers can recommend changes in procedures. Care is taken to display the plant's operating date so that everyone knows how the plant is doing. Employees work with suppliers and customers and have the opportunity to participate in trade shows and visit installation sites. A yearly bonus, equivalent to 15 percent of regular pay in 1996, is based on both individual achievement and team performance [10].
- Sun Life Assurance Society PLC, an insurer, has eliminated most middle management and reorganized once-isolated customer service representatives, each of whom was in charge of a small part of processing a customer's files. Teams now handle jobs from start to end, with a result of reducing turnaround time to settle claims by half, while new business grew 45 percent [11].

Resolution of Short-Term Initiatives

Sometimes operational or short-term initiatives come up that require an interdisciplinary approach in their resolution. The appointment of an ad hoc team to study, analyze, and make recommendations concerning these initiatives becomes necessary.

Some examples of such initiatives where interdisciplinary teams were used include

- Evaluation of a company's procurement policy that resulted in a centralization of the procurement function for common items of equipment and supplies.
- Development of a "continuous performance improvement process" by a team at an electrical utility. The process was developed by a joint union-management team, which talked and worked with hundreds of employees before making recommendations on how organizational processes could be improved in the company. After the process was launched, another joint union-management team was charged with the responsibility to oversee the evolution and maturation of the process in the company.
- An ad hoc team was appointed by an electrical products manufacturer to study and make recommendations for an improved merit and promotion evaluation program. The team did benchmarking with other companies, studied the literature on the subject, interviewed company employees, and worked with a couple of consulting companies in reaching their decisions regarding the changes that should be instituted in the current evaluation program.

Quality Improvement

The use of teams in total quality management (TQM) has enjoyed considerable acceptance in contemporary organizations. These teams can facilitate quality management and productivity improvements, improve labor-management communication, and improve job satisfaction and the quality of worklife for employees. Some of the companies that have been notably successful in setting up superior TQM programs include L.L. Bean, Caterpillar, General Electric, the Boeing company, and the Exxon company to name a few.

An example follows:

- At the Chevron company, a major oil refiner, a "best-practices" discovery team was formed in 1994. It consisted of 10 quality-improvement managers and computer experts from different functions of the enterprise to include oil production, chemicals, and refining. The team uncovered numerous examples of people sharing best practices. After a year of operation the company published a best-practice resource map to facilitate the sharing of knowledge across the company. The map contains brief descriptions of the various official and grassroot teams along with direction on how to contact them. The map and its information helps to connect people working on diverse things in the diverse company [12].

New Business Development Initiatives

The use of interdisciplinary teams to provide a focus for product development, production, and launch is growing in popularity. These teams become involved in marketing and sales promotion strategies, selection of distribution channels, inventory levels, customer training, and an ongoing measurement of the firm's ability to meet customers' needs on a timely and quality basis. These teams can have responsibility for the development of financial strategies, including estimates and tracking of revenues, costs, and likely profit contributions of the product(s).

- At the Gillette company, currently more than 40 percent of sales have come from new products over the past 5 years. This remarkable track record has been accomplished by teams who know how to manage product development projects from ideas through successful product launch. The company's new products are typically those that represent significant improvements. This incessant attention to innovation has been the primary mover of the company's innovative product lines, beyond just razors and blades, such as the Duracel battery acquisition. The company is cannibalizing its current products, assisted by the innovative and effective use of project management techniques and processes to create new products and services [13].

THE PERSONAL IMPACT OF TEAMS

Careers are impacted by the growing use of project and alternative teams in the design and execution of organizational initiatives. In the future, promotion of people will be shaped less by tenure in a given company's hierarchy and more by what the individual has done in his or her career. Adaptive, rapidly changing organizational designs using alternative teams will be used more frequently in which the individual's credentials will be determined by how well he or she works with diverse individuals from within the organizational hierarchy and with outside stakeholders. Team managers and members will be used to acquire resources from diverse sources and put these resources to work developing new products, services, and organizational processes. Team management has become an important cauldron in which careers are formed as the people on these teams have usually been placed there because of a special talent and capability they bring to the enterprise team. Those team members that have made notable contributions in creating something new for the enterprise, such as a new product, service, or organizational process or capability, will be the elite from which new managers are selected. What will be the special capability of these new managers? They will

- Have demonstrated competence in working with diverse groups of people in the enterprise and stakeholders in the company's environment
- Have sufficient technical skills, such as engineering, procurement, manufacturing, and so on, to be noticed as those who produce quality results in their professional lives
- Be able to understand how the enterprise makes money and be able to use the enterprise's resources to achieve revenue producing results
- Know people and communication skills—how to communicate, to network, to build and maintain alliances, how to build the team, and how to use empowerment as a means of exercising authority in the enterprise
- Have the motivation to seek careers in the project management arena where new initiatives to better the enterprise are being forged
- Recognize and accept that what facilitates a career is the impact that the individual has on the organization, and not that person's title [14]

SUMMARY

Alternative teams are increasingly used to provide for an organizational focal point through which product, service, and organizational process change can be managed. The use of teams facilitates the management of both operational and strategic change in the enterprise. When properly used, alternative teams can provide the databases that are needed to help the decision makers in the enterprise choose a course of action that best serves the purpose of the enterprise's mission, objectives, and goals. These end purposes, when properly established and executed, provide key standards of performance for the enterprise.

The major points that have been described in this chapter include the following:

1. Alternative teams are becoming key organizational designs to deal with product, service, and process change in contemporary organizations.
2. The theory and practice of traditional project management provides insight into how and why teams can be used in the management of the organization.
3. Although alternative teams are much like traditional project teams, there are differences that have been described in this chapter.
4. Industrial engineers, by virtue of their education and typical experience, are well suited to become leaders of alternative teams in today's organizations.

5. *Fortune* magazine has stated that the ability to organize employees in innovative and flexible ways and the enthusiasm with which so many American companies have deployed self-managing teams is why U.S. industry is so competitive.

6. A summary of the key results that teams produce was presented in the chapter. The reader will note that these results usually relate to both operational and strategic initiatives of the enterprise.

7. Many of the alternative teams described in this chapter are ad hoc in nature but are part of an ongoing strategy for dealing with operational and strategic change.

8. The opportunity to serve on alternative teams provides excellent on-the-job training in leadership skills and attitudes.

9. The use of alternative teams is clearly an idea whose time has come.

10. Many of the alternative teams in use today draw on the lessons learned in the development of the theory and practice of traditional project management.

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BIOGRAPHY

David I. Cleland, Ph.D., is currently professor emeritus at the School of Engineering at the University of Pittsburgh. Also an honored Fellow of the Project Management Institute (PMI), he is the author of 31 books and dozens of articles for leading national and international journals. On September 29, 1997, Dr. Cleland was honored by having a new PMI award named for him—the David I. Cleland Excellence in Project Management Literature Award.

CHAPTER 2.6

INVOLVEMENT, EMPOWERMENT, AND MOTIVATION

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This chapter discusses the changing role of the industrial engineer from technical expert to team leader, coach, and motivator. An emphasis is placed on understanding how involving and empowering employees can be powerful motivators in affecting productivity. Additionally, practical examples are provided that allow the industrial engineer to better understand the use of these concepts to affect and improve productivity. Finally, this chapter addresses the importance of motivation, involvement, and empowerment to the industrial engineer as we move forward in the twenty-first century.

THE ROLE OF THE INDUSTRIAL ENGINEER—PAST AND PRESENT

What is your idea of the role of the industrial engineer? If you think of plant layout, work measurement, time and motion studies, and production and inventory control, you may need to rethink your perspective. In a 1971 survey conducted by the Institute of Industrial Engineers (IIE), with the results detailed in the third edition of the *Industrial Engineering Handbook,* edited by H. B. Maynard, these were the topics highlighted as the key activities for the industrial engineer. Although these responsibilities continue to be important, the role of the industrial engineer includes many different facets as we go forward in the twenty-first century.

Since the 1971 survey, industrial engineers (IEs) have taken on a much broader role. Today, it is not uncommon for an engineer to be part of a team that includes supervisors, hourly workers, quality specialists, trainers, and other engineers. This team could exist in a manufacturing, distribution, or retail environment. The responsibilities of the industrial engineer on that team could include systems analysis, advanced statistics, training facilitation, and simulation. With all of the different responsibilities, teams, and environments that an industrial engineer affects, what is most interesting about today's industrial engineer is that he or she probably takes on the role of change agent, team leader, motivator, and employee involvement program coordinator. An article by Eric Minton describes how the role of the traditional industrial engineer has changed to team member of a manufacturing excellence team in one company. "The IE used to focus on methods improvements, time studies, manpower standards, workplace layout, tooling, and fixtures. Today the manufacturing excellence team's mission is to simply do any and all things that help the company achieve its vision of becoming a world-class manufacturing company" [1].

With the renewed focus on doing whatever needs to be done to increase productivity, it is increasingly important for the industrial engineer to understand how his or her role can contribute to the company achieving its vision. The industrial engineer may not directly work on the product being manufactured, but plays a key role when working with employees who do. In the past, industrial engineers often did not involve line operators when making improvements. In today's workplace, teams made of different functional groups contribute to the improvement ideas and their implementation. Matthew Kline points out in *Industrial Engineering Solutions* that many companies have attempted continuous improvement efforts and have failed for a variety of reasons. He states that "for the vital few who are revisiting their continuous improvement effort with the hope of not repeating their mistakes, expanding the IE's role and responsibilities is crucial" [2].

Customers want products and services better, cheaper, and faster. Companies are addressing these issues with teams—cross-functional teams, continuous improvement teams, special interest (task) teams, and quality teams. Most companies realize that as they move forward with teams the role of the industrial engineer must be expanded to include not only the traditional technical skills, but also the softer team-oriented skills. An August 16, 1998, article from *Industry Week* summarizes that the best managed companies know "that having good quality products is no longer an advantage; it's a given." To even be considered as one of *Industry Week's* 100 Best Managed Companies a firm must be strongly committed to education, employee empowerment, teams, and employee involvement [3]. The industrial engineer is now being called on to support these principles.

The industrial engineer of today needs to understand how his or her actions can affect the motivation of the workforce. He or she plays a key role in motivating the workforce by knowing how and when to involve and empower employees. In an article Gregory Hutchins wrote for *Industrial Engineering Solutions,* he describes how the role of the IE is changing "from one who is responsible for monitoring, improving, and controlling operations to a broader role." He goes on to list the three areas he feels will emerge for the industrial engineer: process/project management, technology management, and people/team leadership [4]. Businesses have long recognized the need for project and technology management. However in recent years, it can be shown both statistically and in practice that a key to becoming a world-class organization is the ability of a company to empower, motivate, and train its workforce.

INVOLVING EMPLOYEES

General Definition

The most valuable commodity in today's economy is not a durable metal or expansive machine—it is people. Consider the words of Samantha Wilson, a production stamper at Wilson Sporting Goods Company: "When I first found out what the words 'you make a difference' really meant, I started to feel different about my job. Knowing that I had a say made me like my job more. I felt that I was more involved and trusted, and I like working for a company that trusts me" [3].

It is commonly understood that someone who does the job knows the job best. It also stands to reason then that this person may have the best suggestions for making improvements and modifications. Involving others in activities that relate to them gives them a sense of ownership. This ownership helps to build the motivation and commitment of the worker.

Consider this example. You are asked to participate on a team to improve the packaging of a product. You expect that you will be asked for your ideas since you have been working in the shipping department for four years. When the team gets together, the team leader assigns roles to each team member and suggests that each person collect information and return for next week's meeting. When you return you have collected information and are ready to share your great ideas on how to change the packaging. You arrive at the meeting, ideas in hand. Instead of sharing those ideas, the team leader collects the information and thanks everyone and concludes the meeting. The team leader then prepares a report and forwards it to management who approves the suggested changes and the new packaging begins. Some of your ideas were used on this project, others weren't, but yet you are expected to be excited about all of the new improvements. How does this make you feel? Are you motivated to do your work? Will you be excited the next time you are asked to participate on a project?

As a team leader, it is imperative for the industrial engineer to understand the meaning of involvement. Involvement means asking people to participate and listening to what they have to say—not simply asking for their ideas. It is getting them involved in those ideas and letting them take ownership of those ideas.

Involving employees results in:

- Increased motivation and participation
- Better communication (people are willing to share information and knowledge)
- Better commitment
- Higher trust levels
- A new sense of cooperation, responsibility, and ownership
- Development of technical and interpersonal skills
- The realization that the person doing the job understands all facets of the job and can contribute where others cannot

There are many ways of involving employees such as asking for their opinion, including them in a group discussion, asking for their improvement ideas through an employee involvement program, and having them participate on teams.

Involving Employees Through Teams

Participating in teams is an extremely effective technique for involving employees. As team leader, the industrial engineer needs to bring pertinent staff members into the decision-making process. This will not only make the final decision better, it also tends to build more support for the eventual outcome. A team could be a cross-functional team brought together for a specific project or task. The organization could be designed to have employees work in teams on a regular basis or for a specific project and task. In either case, involving employees in the day-to-day activities of the company has shown long-term benefits for many organizations. The training that employees need to go through to fully understand the team concepts and the teamwork used every day stays with them long after they step out of the training room. Working in a team culture can improve morale, increase productivity, and retain employees. How can teamwork do so much?

Teamwork creates synergy and allows employees to accomplish more as a group than they would individually. Participating on a team also allows employees to step out of their regular routine and contribute ideas more freely. And it is often simply more fun to work in a group than alone.

Understanding team concepts can help the industrial engineer lead, motivate, and empower his or her team when the time is right. The skills needed to lead and participate on a team are listed below:

- Team concepts
  - What makes a team
  - The stages of team development
  - Dealing with conflict
  - Leading meetings
  - Giving feedback
  - Communication (giving and listening)
- Coaching skills
- Knowledgeable in technical area (increases credibility)
- Knowledgeable about company issues/policies to know how changes may affect company
- Committed to team

It is key that the team leader is committed to the team, but how can buy-in be created for the team members? One way to get their commitment is to create a team charter when a team is started. The team charter outlines the scope of a project and identifies roles, responsibilities, and guidelines that the team will follow. Creating a charter and involving employees in the decision making of a project gains their commitment to that project. Figure 2.6.1 provides an example of a team charter.

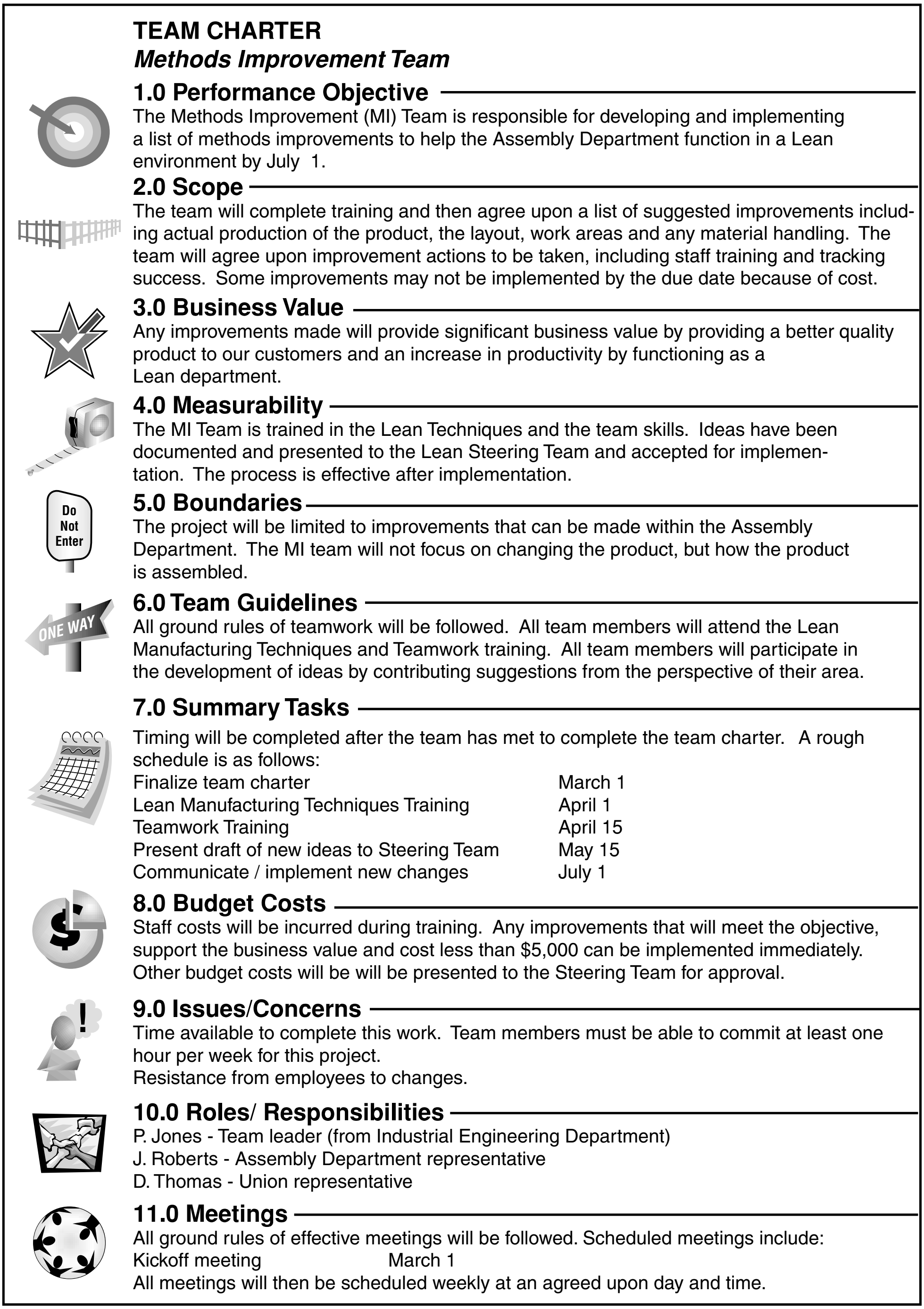
Employee Involvement Programs

Structured employee involvement programs are a more formal way to involve employees. Employee involvement programs can be used in conjunction with or in place of traditional suggestion systems. The traditional suggestion system focused on receiving ideas, often anonymously, to help the company with its continuous improvement efforts. Today's involvement programs take the suggestion system one step further by including the employee who submitted the idea in the review and implementation of the idea. Employee involvement programs are designed to collect ideas from employees to improve revenue, conserve costs, or create a better place to work through continuous improvements. The program gives the employee a voice in making suggestions. It has been shown that employee involvement programs can reap great rewards. When employees contribute ideas to a company and then have the responsibility for implementation, these people feel like they have made a difference.

The following are guidelines that should be used when developing an employee involvement program:

1. *Ensure top management's commitment.* Without the commitment from upper management, the program is doomed to fail from the start. Employees need to see that management is supportive and participating in the employee involvement program for the program to work.
2. *Determine the objective for the program.* The objective can be broadly stated, such as "The objective of the employee involvement program is to provide every employee with the opportunity to participate in improving how the company operates" or "This program supports our continuous improvement efforts by providing a vehicle for your ideas." Without an objective, employees will not know why the company is establishing the program. Identifying and communicating the objective helps to build commitment with the employees.
3. *Select a team of employees to represent the company or have employees volunteer to be on the team.* The employees should be from different departments so that the group has a broad perspective. The size of the team should be approximately 6 to 10 people. The team of employees is responsible for collecting, analyzing, and following through with ideas as well as for the ongoing success of the program.

INVOLVEMENT, EMPOWERMENT, AND MOTIVATION



TEAM CHARTER

Methods Improvement Team

1.0 Performance Objective

The Methods Improvement (MI) Team is responsible for developing and implementing a list of methods improvements to help the Assembly Department function in a Lean environment by July 1.

2.0 Scope

The team will complete training and then agree upon a list of suggested improvements including actual production of the product, the layout, work areas and any material handling. The team will agree upon improvement actions to be taken, including staff training and tracking success. Some improvements may not be implemented by the due date because of cost.

3.0 Business Value

Any improvements made will provide significant business value by providing a better quality product to our customers and an increase in productivity by functioning as a Lean department.

4.0 Measurability

The MI Team is trained in the Lean Techniques and the team skills. Ideas have been documented and presented to the Lean Steering Team and accepted for implementation. The process is effective after implementation.

5.0 Boundaries

The project will be limited to improvements that can be made within the Assembly Department. The MI team will not focus on changing the product, but how the product is assembled.

6.0 Team Guidelines

All ground rules of teamwork will be followed. All team members will attend the Lean Manufacturing Techniques and Teamwork training. All team members will participate in the development of ideas by contributing suggestions from the perspective of their area.

7.0 Summary Tasks

Timing will be completed after the team has met to complete the team charter. A rough schedule is as follows:

Finalize team charter	March 1
Lean Manufacturing Techniques Training	April 1
Teamwork Training	April 15
Present draft of new ideas to Steering Team	May 15
Communicate / implement new changes	July 1

8.0 Budget Costs

Staff costs will be incurred during training. Any improvements that will meet the objective, support the business value and cost less than $5,000 can be implemented immediately. Other budget costs will be will be presented to the Steering Team for approval.

9.0 Issues/Concerns

Time available to complete this work. Team members must be able to commit at least one hour per week for this project.

Resistance from employees to changes.

10.0 Roles/ Responsibilities

P. Jones - Team leader (from Industrial Engineering Department)
J. Roberts - Assembly Department representative
D. Thomas - Union representative

11.0 Meetings

All ground rules of effective meetings will be followed. Scheduled meetings include:

Kickoff meeting	March 1

All meetings will then be scheduled weekly at an agreed upon day and time.

FIGURE 2.6.1 Team charter.

4. *Develop a processing system for ideas.* The processing of ideas includes the submission of the idea through implementation of the idea if it is deemed feasible and valuable to the company. It is very important that employees understand what level of decision-making authority they have in implementing ideas. Some companies give all employees an approval limit on any idea. Five thousand dollars is a reasonable limit for many companies. This means that if any employee has a constructive idea that helps to meet the objective of the program that can be implemented for $5,000 or less, they have the authority to do it. This type of involvement boosts morale as employees can contribute ideas to make their company a better place, but more importantly they have been empowered to act on their ideas. Developing a flowchart of the process is a visible and clear-cut means for employees to understand the process. An example flowchart of this process is shown in Fig. 2.6.2.

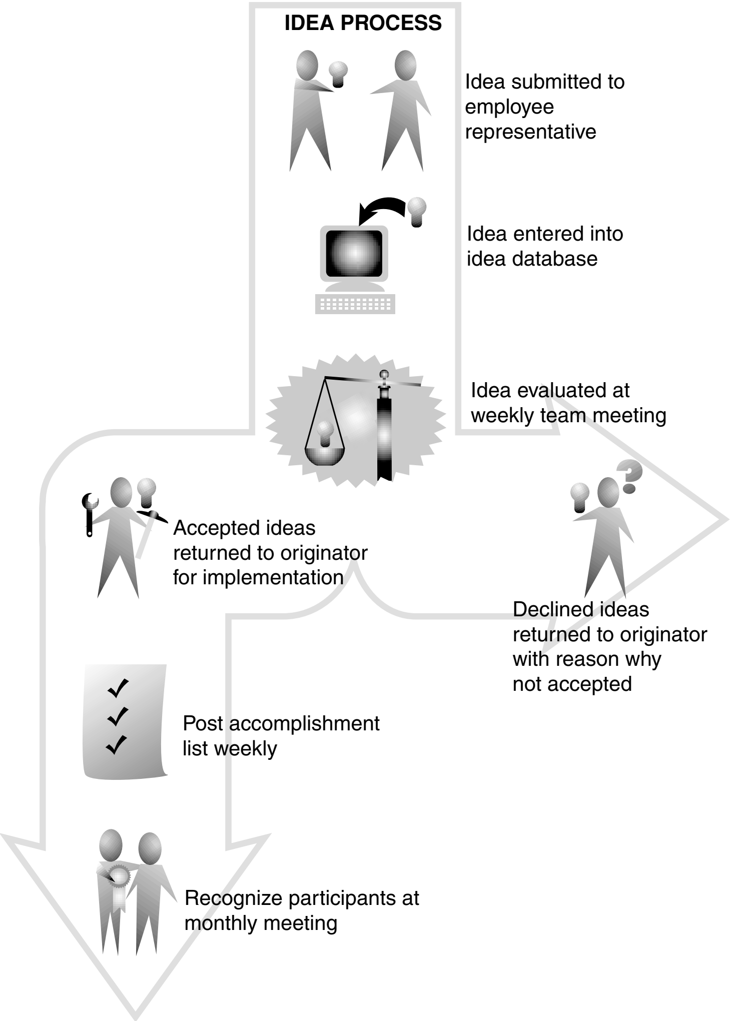

IDEA PROCESS
Idea submitted to employee representative
Idea entered into idea database
Idea evaluated at weekly team meeting
Accepted ideas returned to originator for implementation
Declined ideas returned to originator with reason why not accepted
Post accomplishment list weekly
Recognize participants at monthly meeting

FIGURE 2.6.2 Idea process.

5. *Develop a reward and recognition program for ideas.* Many companies use rewards in helping to generate ideas. Examples of rewards could be company hats, T-shirts, or cash.
6. *Communicate the program to employees.* This communication should come from the president of the company to show management's commitment and should be lively and upbeat. The kickoff meeting should explain the objectives of the program as well as the procedures for submitting an idea. If this type of program is very new to employees, help them to start thinking of ideas by giving them questions to think about, such as "What can I or my department do to reduce costs without negatively impacting quality?" or "What changes can I make to better service our clients?" or "What can be done to increase safety?"
7. *Develop a plan to make the program ongoing and visible to employees.* This plan could include hanging posters about the program, distributing the completed idea list, and holding monthly meetings to review ideas and reward participants.
8. *Follow up with employees for understanding and ideas.* This could be done individually or at a company meeting.

An industrial engineer is often a key player in a company's employee involvement program, but does not have sole responsibility for the success or failure of the program. The industrial engineer, however, is integral to the program as he or she often has an active role in the implementation of an idea to improve a process. A recent survey supports the notion that more than industrial engineers are needed for a successful program. In a recent survey done for the Kentucky Labor Cabinet's Office of Labor Management Relations and Mediation, the following factors contributed to the success of a program. They are listed in descending order of importance.

- Support by top and middle managers and first-line supervisors
- Worker education and training
- Available resources
- Union support
- Decentralized decision-making authority
- Employment security
- Monetary rewards

The following items were listed in the survey as the biggest barriers to a successful employee involvement program:

- Unclear objectives
- Management opposition to employee involvement
- Lack of training
- Lack of champion for employee involvement
- Lack of long-term strategy
- Centralized decision-making authority
- Lack of union support
- Lack of tangible improvements
- Short-term performance pressure
- Lack of program coordination
- Top management turnover
- Worsened business conditions

Involvement and Productivity

Involving employees with employee involvement programs has been credited for reducing costs and improving productivity in many companies. In 1993, Exxon's employees averaged 12 improvement ideas per person. The results are impressive: administrative costs dropped by 17 percent and between 1989 and 1993 productivity increased by 30.5 percent [5].

For the concept of involving employees to work, the company must have management buy-in. The highly involved workforce for many is a cultural change and it needs to start at the top. In summary, at a minimum, involvement means that everyone's voice is heard and that all ideas and opinions are considered.

Practical Tips About Involvement

Figure 2.6.3 illustrates some practical dos and don'ts about involvement.

EMPOWERMENT

General Definition

Who takes responsibility for you getting up each day? Who takes responsibility for you to be able to buy a house, pay your bills, or go on vacation? The answer, of course, is you. You take responsibility for your own actions in life. You are empowered to make and act on your personal decisions. The same concept of empowerment is used in the workplace. Empowerment means that individuals are given the authority to make decisions and act on them.

In the best-selling business book, *Zapp!,* William C. Byham writes that "empowerment is helping employees take ownership of their jobs so that they take personal interest in improving the performance of the organization" [6]. When people take ownership and responsibility of a task or project, buy-in and commitment are much higher. They feel like they make a difference. Empowerment is giving employees the authority to stop a process in action if they see a quality problem or safety risk. At Verilink Corporation, a San Jose–based manufacturer of telecommunications equipment, every production worker is cross-trained to do everyone else's job. This has eliminated the need for middle management. All of Verilink's production workers are accountable for what each produces. And because workers review each other's work, there are virtually no production errors. Simply put: Verilink's employees rely on a system of trust and empowerment to excel in their industry.

Empowerment Pays Dividends

Employee empowerment pays. It produces greater employee loyalty and job satisfaction, higher productivity, increased profits, and better products. The January 1998 edition of the *Harvard Business Review* sites a Sears Company executive as saying that "a 5 percent improvement in employee satisfaction correlates to a one-half of 1 percent increase in revenue" [7].

Of course, simply saying that employees are empowered is not enough. Companies also have to demonstrate an investment in the activities that make empowerment a reality. These include trust, teamwork, training, decentralization, and linking employee performance to measurable business results.

For the industrial engineer to stay involved with employees, he or she needs to understand the concept of empowerment and the key principles of empowerment. These three key principles were developed by Byham with Development Dimensions International:

1. *Maintain and enhance self-esteem.*
   When working with employees it is always important to maintain or enhance their self-esteem. If they have an idea that seems inappropriate, it is very important not to shoot them down but to listen through the idea and thank them for taking the time to think of the idea, and then explain why the idea will not work at the time.
2. *Listen and respond with empathy.*
   Employees often need someone to listen when they have a problem they feel they cannot do anything about. It is important to listen to them and then acknowledge that you can understand their frustration and will do what you can to help.
3. *Ask for help and encourage involvement.*
   This last principle is critical in developing an empowered workforce. In today's environment very few people work solely by themselves. Being assigned a project or responsi-

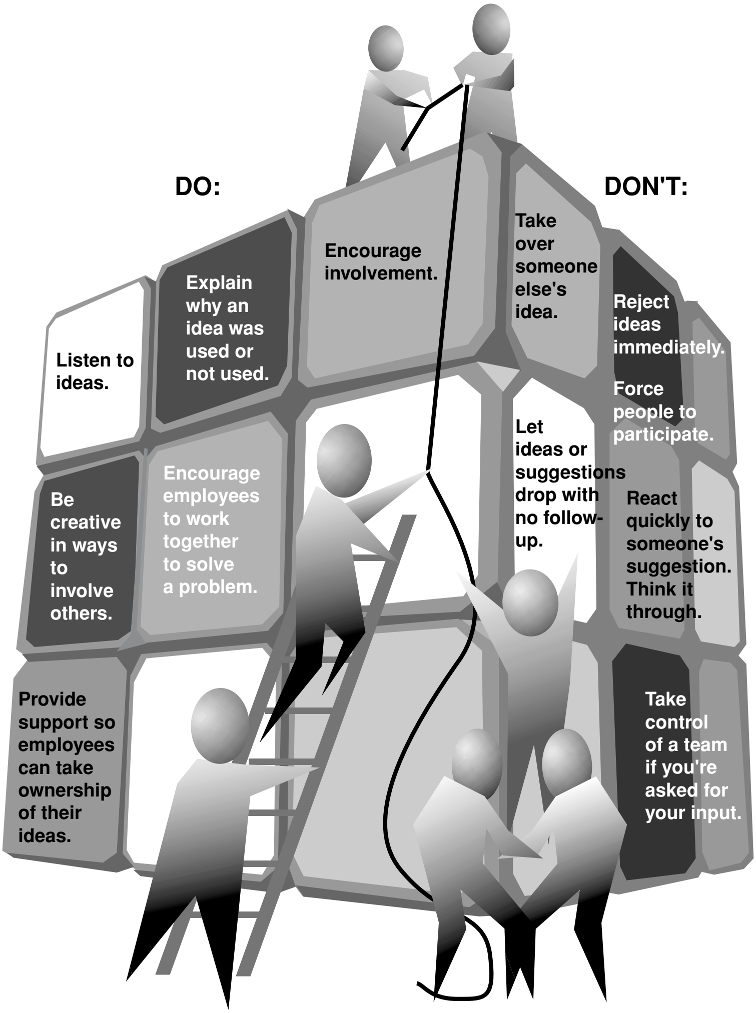

DO:
DON'T:
Listen to ideas.
Explain why an idea was used or not used.
Encourage involvement.
Be creative in ways to involve others.
Encourage employees to work together to solve a problem.
Provide support so employees can take ownership of their ideas.
Take over someone else's idea.
Reject ideas immediately.
Force people to participate.
Let ideas or suggestions drop with no follow-up.
React quickly to someone's suggestion. Think it through.
Take control of a team if you're asked for your input.

FIGURE 2.6.3 Tips for involvement.

bility does not mean you cannot ask for help. Asking for help from others shows that you respect their skills and ideas. Asking for help shows that you trust their opinions and will build commitment to the project.

In the book *Heroz,* Byham describes the importance of personal empowerment in this way: "These days, the organization that wishes to remain competitive needs more than a few heads at the top of the organization working on ways to improve performance. It needs the involvement of those working nearest to the customer and of those who are actually creating the value the customer is paying for. Empowerment is the best way to gain that involvement" [8].

Empowerment and Productivity

Employees that are empowered to make decisions do not waste time searching for a supervisor to get approval. They take action as needed and get back to work as soon as possible. An empowered environment results in employees taking responsibility for their own success, thereby ensuring the company's success.

Practical Tips About Empowerment

Practical dos and don'ts about empowerment are depicted in Fig. 2.6.4.

INVOLVEMENT, EMPOWERMENT, AND MOTIVATION

General Definition

As indicated previously, the role of the industrial engineer is changing fast. Gone are the days of the industrial engineer working in his office with pencil and pad, sketching details. Today, the industrial engineer is on the floor working with employees to make changes. He or she may be part of a team assigned to improve the output of a line. The industrial engineer may be part of a team to reduce shipping costs. In either case, the industrial engineer is part of a team and many times the leader of the team.

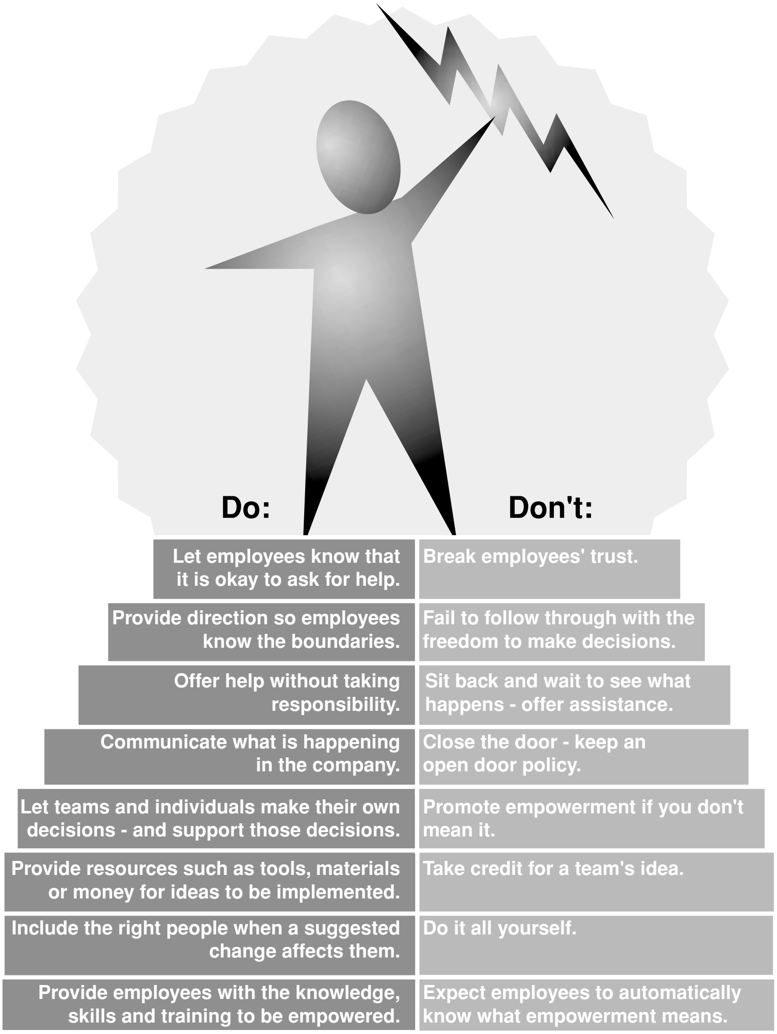
When leading a team, the leader needs to know the makeup of the team. What do they do? How long have they been with the company? What are their skills and preferences? What inspires the team and what does not? The answers to these questions will help the industrial engineer decide how to motivate his or her team. He or she needs to find out what inspires them to do better. We all want to do the best job we can, but what motivates each of us to do that? It could be money or recognition. It could be self-satisfaction that you did a good job. It could be knowing that what you do impacts several others. According to the authors of *Succeeding with Teams,* "research on motivation consistently shows that, far more than cash, what really pleases people is being noticed and complimented—most often visibly—for a job well done" [5]. The industrial engineer needs to know what motivates the groups that he or she is working with and then how to motivate them.

Five Factors That Motivate

Five primary factors affect the motivation of most individuals. These factors are

1. *Motives.* The industrial engineer needs to determine what the worker's motives are. Does the person want power, affiliation with a group, or recognition for an achievement?

INVOLVEMENT, EMPOWERMENT, AND MOTIVATION



Do:	Don't:
Let employees know that it is okay to ask for help.	Break employees' trust.
Provide direction so employees know the boundaries.	Fail to follow through with the freedom to make decisions.
Offer help without taking responsibility.	Sit back and wait to see what happens - offer assistance.
Communicate what is happening in the company.	Close the door - keep an open door policy.
Let teams and individuals make their own decisions - and support those decisions.	Promote empowerment if you don't mean it.
Provide resources such as tools, materials or money for ideas to be implemented.	Take credit for a team's idea.
Include the right people when a suggested change affects them.	Do it all yourself.
Provide employees with the knowledge, skills and training to be empowered.	Expect employees to automatically know what empowerment means.

FIGURE 2.6.4 Tips for empowerment.

2. *Situation.* The industrial engineer needs to identify the culture, work environment, and job characteristics to better understand the worker's situation.
3. *Mind.* The industrial engineer needs to identify what each worker's expectations are. Are there incentives or status involved?
4. *Heart.* The industrial engineer needs to identify what the worker enjoys and prefers doing. Does the worker see this task as a challenge or an obstacle?
5. *Self.* The industrial engineer needs to understand how the worker views his or her skills and abilities. Is this task good for the worker's self-esteem?

Considering these five factors will help the industrial engineer to determine the right job for each worker, ensuring a motivated workforce. The industrial engineer can also look at these factors to better understand his or her own intrinsic motivators. Do you like helping others? Do you like to see tangible improvements? Is it the culture of the company that makes you want to go to work? What are your expectations for the job? What are you really good at and what do you enjoy doing? Answering these questions will help the industrial engineer to better understand what it is he or she likes to do and why, thus understanding what motivates him or her.

Motivational Techniques

The industrial engineer can use different techniques (commendations, tangible items, verbal recognition, pat on the back) to make people feel good about what they are doing. Motivation can also result from employees feeling that they are involved in the organization and empowered to make and act on decisions.

Try using one of the following motivational techniques on your next project:

- Treat everyone equitably.
- Use verbal recognition—tell someone they did a good job and why. Tell them in front of everyone at a team meeting.
- Write a memo or e-mail about a job well done and why. Copy the person's boss and make sure it gets put into their personnel file.
- Create reward programs—give away company caps or T-shirts.
- Give awards—hang a ribbon near a person's work area highlighting his or her accomplishments. Use a ribbon or certificate that says "Great Effort" or "Most Improved," for example.
- Have someone wash an employee's car during the workday.
- Buy lunch for the team—buy lunch at a nearby restaurant or have lunch brought in.
- Have a party—celebrate the accomplishments of a team with an afternoon celebration. Have cake and banners ready.
- Display banners—hang a banner in the work area that says "Congratulations," or some other form of recognition.
- Distribute gift certificates—gift certificates can be given to restaurants or a company store.
- Give money—monetary recognition will almost always work.
- Make an announcement highlighting individual or team contributions at the next company meeting.
- Use the company newsletter to highlight the accomplishments of the team.

Motivation and Productivity

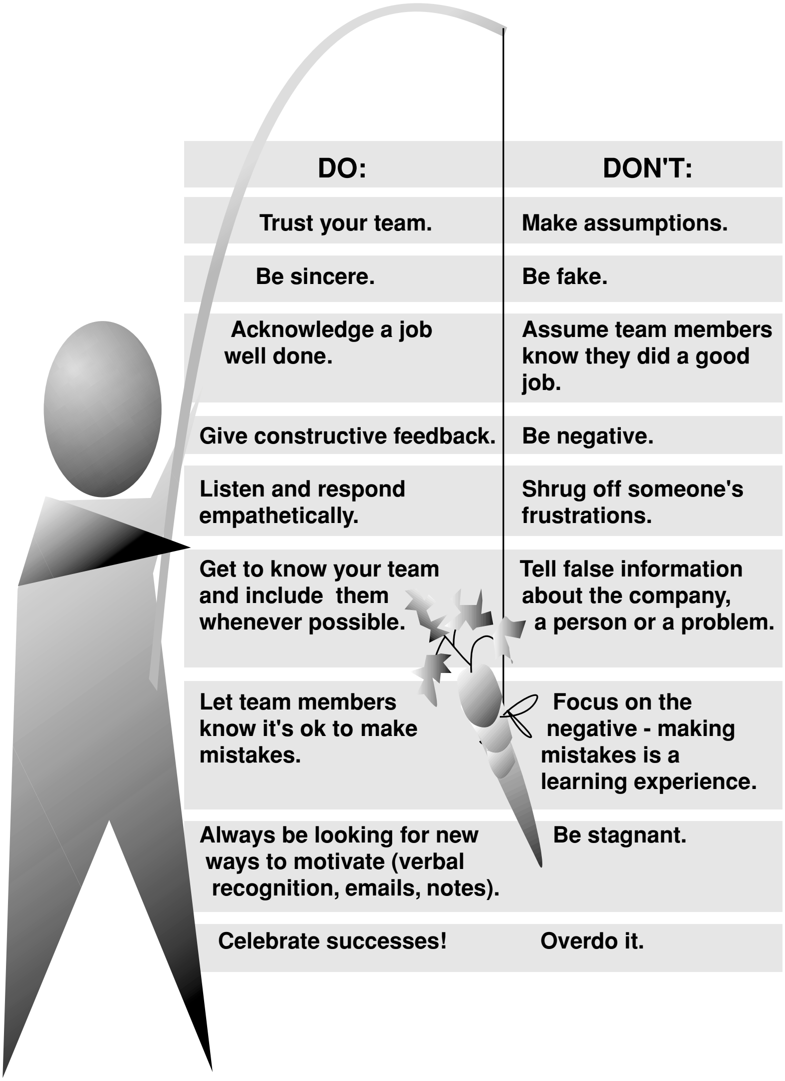
In *A Better Place to Work,* Adolf Haasen and Gordon F. Shea state that the "motivational structure of a group strongly influences the group's productivity" [9]. A team comprised of motivated workers—workers who have the ability to carry out meaningful tasks that require multiple skills and have a collective responsibility for the outcome—will have an increased level of productivity and output.

To develop a motivated workforce, the industrial engineer must be a source of experience and expertise, earning the trust and respect of the workforce as a role model for the organization. The industrial engineer should be able to develop strategies, provide vision, coach, and mentor, as well as become the "anchor" for the team.

Practical Tips About Motivation

Motivation dos and don'ts are depicted in Fig. 2.6.5.

INVOLVEMENT, EMPOWERMENT, AND MOTIVATION



DO:	DON'T:
Trust your team.	Make assumptions.
Be sincere.	Be fake.
Acknowledge a job well done.	Assume team members know they did a good job.
Give constructive feedback.	Be negative.
Listen and respond empathetically.	Shrug off someone's frustrations.
Get to know your team and include them whenever possible.	Tell false information about the company, a person or a problem.
Let team members know it's ok to make mistakes.	Focus on the negative - making mistakes is a learning experience.
Always be looking for new ways to motivate (verbal recognition, emails, notes).	Be stagnant.
Celebrate successes!	Overdo it.

FIGURE 2.6.5 Tips for motivation.

MOVING FORWARD

Having a highly motivated, involved, and empowered workforce does not happen overnight. And it does not happen without communication and training. You cannot expect employees to understand teams, how they work, or what constraints there are without training. As the role of the industrial engineer changes, it is important to keep in mind that some engineers will change and adjust their actions and approach to work naturally. However, many engineers will need training. It takes training and practice to learn how to motivate another person.

For the industrial engineer to have support as a coach or team leader, there must be management buy-in. The role of the industrial engineer has changed and in many instances so has a company culture. Management needs to support these changes and support the industrial engineer in carrying out these changes.

If your organization is changing or, worse yet, has not changed in 20 years, ask yourself the following questions.

- What is the culture and has it changed?
- Why do you want to involve workers?
- Is upper management in full support?
- How will you train employees on team concepts?
- How will follow-up be done to reinforce concepts?

The answers to these questions are important if your organization is interested in having a highly involved workforce. The twenty-first century is very challenging with worldwide competition. The pressure is on every organization to reduce costs and improve productivity, and the industrial engineer cannot do it alone nor is he or she expected to anymore.

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BIOGRAPHIES

Therese Mylan is the Knowledge Center manager for H. B. Maynard and Company, Inc., in Pittsburgh, Pennsylvania. Her career spans 17 years in several industries including engineering, software, manufacturing, technical writing, and technical training. She has been with Maynard since 1994. Mylan holds a bachelor's degree in technical writing and English from

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CHAPTER 2.7

ENGINEERING ETHICS: APPLICATIONS TO INDUSTRIAL ENGINEERING

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Industrial engineering decisions may involve factors such as environmental pollution, product safety, and workplace hazards. In addition, such decisions may be made under cost and schedule pressures. These factors contribute to increased risks, which in turn can lead the engineer and the organization into an ethical dilemma. How such dilemmas can occur in practice is discussed and a framework for both the practicing engineer and the engineering organization to help avoid these situations is presented. The framework emphasizes the importance of competence, responsibility, and avoidance of harm (reducing risk). A particular emphasis is placed on risk assessment and the need for industrial engineers to add the evolving methodology of risk assessment, especially probabilistic risk assessment, to their toolkit.

WHY SHOULD THE IE BE CONCERNED ABOUT ETHICS?

Introduction

Why should an industrial engineer (IE) be concerned about ethics? As Stewart and Paustenback pointed out 15 years ago, engineers must make decisions that may involve such factors as environmental pollution, product safety, and workplace hazards. They noted that this takes managers into areas where even the most carefully considered decisions are likely to be criticized. Further, the data and even the knowledge bases they must rely on may be incomplete or equivocal. Hence, decisions with ethical or moral dimensions may prove to be more troublesome than decisions that primarily involve issues of finance, marketing, or production. Yet, ignore such issues and the long-term survival of the firm can be jeopardized [1]. We call such situations ethical dilemmas, and they may arise in a number of ways, many unexpected.

Four Examples of Ethical Dilemmas

What are some examples? Here are several that we found in the *Pittsburgh Post Gazette* and the *New York Times* over a three-day period in November 1997:

- "Apparel Panel Badly Divided on Policing of Sweatshops." A presidential task force to establish a code of conduct for apparel factories found itself fighting over how much the public should be told when inspectors discover labor violations in factories. The task force (whose members represented labor unions, human rights groups, and corporate giants) had earlier agreed to limiting the workweek to 60 hours and the minimum age to 14. Imagine being the IE charged with designing or managing an offshore facility that uses child labor in order to minimize costs. What moral and ethical issues would you have to struggle with?
- "House Ethics Charade." After two years of charges, the House Ethics Committee has finally gotten around to investigating Congressman Bud Shuster. Among the issues is the congressman's habit of combining official trips and campaign fund-raising, thus creating the impression that Shuster's support for local transportation projects is for sale. Should you, as a manager with the municipal transportation authority seeking federal funds for a new highway project, invite the congressman to town for one of these dual-purpose trips?
- "Fiber Optics for Jets." An informed letter writer commenting on faulty wiring being the most likely triggering mechanism for the TWA Flight 800 disaster has called for a new investigation: Why are aircraft designers using copper wiring in what are supposed to be state-of-the-art aircraft? Instead, he proposed that fiber optics be used to reduce the probability to near zero of catastrophic failure from frayed and shorted copper wires. As a design engineer on this project, under tight cost constraints, what would you do?
- "29 Nations Agree to Outlaw Bribing Foreign Officials." After years of U.S. lobbying, the world's industrialized countries formally agreed to a treaty that would outlaw bribing foreign government officials. For a long time, American companies have complained about losing billions of dollars in business every year to rivals that bribe officials in order to win contracts. The treaty would not outlaw payments to political party leaders, many of whom may be the central decision makers. In the meantime, the Justice Department has beefed up its investigation into developing markets in Asia where bribes are common. As the overseas manager for an American company competing for business in Southeast Asia, would you be willing to violate U.S. laws in order to obtain an important contract and the promotion that would go with it?

Balancing Cost, Schedule, and Risk

In our recently published book, *Engineering Ethics—Balancing Cost, Schedule and Risk: Lessons Learned from the Space Shuttle,* coauthored with Rosa L. Pinkus and Norman P. Hummon, we studied how engineers perceived, articulated, and resolved ethical dilemmas that arose when complex, advanced technology was developed [2]. In doing this, we explicitly chose not to solely focus on what philosopher Michael Pritchard has termed disaster ethics [3]. That is, those headline events exemplified by the explosion of the Challenger, the Three Mile Island nuclear power plant malfunction, or the recall of the Ford Pinto [4]. Rather, we concentrated on the everyday decisions made by engineers and others that can lead to these ethical dilemmas. This is particularly true for the Challenger disaster, which, we have concluded, was not the result of a single event. Instead, it can be traced to the decision by Congress to fund the Space Shuttle program at a cut-rate price and the acceptance by NASA to proceed with plans to build the shuttle that set the stage for individual engineers to continually struggle to balance safety, cost, and schedule. What we observed was that safety, while always a part of the equation, did not consistently override the other variables.

ENGINEERING ETHICS: APPLICATIONS TO INDUSTRIAL ENGINEERING

We believe that such lessons are especially relevant to practicing industrial engineers. Especially because of the nature of their work, IEs must not only deal with pressures of cost and schedule, but often are the ones responsible for setting those schedule and cost constraints. It is the industrial engineer who typically must decide which schedule is feasible and at what cost. Once the schedule is frozen, the IE must make sure that it is adhered to, and then serve as the first line of responsibility when costs begin to increase or the schedule slips. In doing this, the IE must make assumptions about risk, and how that risk may be increased. Further, he or she must determine when that increased risk is no longer acceptable. All too often, such risk assessments are done implicitly rather than explicitly. So, the ability to assess risk becomes an important tool for the ethical industrial engineer.

ENGINEERING ETHICS AS APPLIED ETHICS

Engineering Ethics—A New Field of Inquiry

The formal field of engineering ethics is relatively new. Although it boasts a growing literature, there is no reflective analytic view of engineering ethics as a discipline. Indeed, Martin and Schinzinger, authors of one of the first and still a leading engineering ethics text, note that "as a discipline or area of extensive inquiry, engineering ethics is still young" [5]. They set its formal beginnings in the late 1970s and cite several landmark events: a first interdisciplinary conference in engineering ethics at Rensselaer Polytechnic Institute and a scholarly bibliography in 1980; and the first scholarly journal, *Business and Professional Ethics,* in 1981 [6]. "This late development of the discipline is ironic," they conclude, given that numerically, the engineering profession "affects all of us in most areas of our lives" [7].

Our approach is that of applied ethics. We wish to sensitize the engineer or engineering student to potential ethical dilemmas, especially those that arise in the daily workplace. In particular, we want the engineer to be able to recognize these developing ethical dilemmas and then be able to structure the issues in a way that first better clarifies them and then facilitates resolution. A prerequisite to this identification and structuring process is a definition of terms commonly used in the field. To do this, we have adopted the following definitions [8].

A few definitions of terms

Ethics A generic term for several ways of examining the moral life (i.e., critical reflection on what one does and why one does it). Some approaches to ethics are descriptive and others are normative.

Descriptive Ethics (non-normative) Factual investigation of moral behavior and beliefs. The study not of what people ought to do but how they reason and how they act.

Normative Ethics (general) The field of inquiry that attempts to answer the questions, Which action guides are worthy of moral acceptance? and For what reasons? Types of action guides are theories, principles, and rules. They are used to assess the morality of actions.

Normative Ethics (applied) The act of applying action guides to normative problems (i.e., professional codes of ethics—role norms/obligations that professions attempt to enforce). Sometimes etiquette and responsibilities are spelled out. Typically, applied normative ethics are not as inclusive as general normative ethics.

Metaethics (non-normative) The analysis of language of crucial ethical terms such as virtue, right, obligation. It examines the logic and the patterns of moral reasoning.

Tacit Ethics Unsaid, unspoken rules of practice.

The Engineer's Multiple Loyalties

In addition to the previously noted cost and schedule pressures, the multiple loyalties of the practicing engineer also lead to ethical dilemmas. There are at least four constituencies that the practicing engineer may be responsible to, and often they are in conflict. Clearly, the engineer has a loyalty to his or her employer (i.e., the organization), but the practice of engineering may also involve a client or contractor, and this creates a second level of loyalty. Then there is the public, where the "safety of the public" as declared by Cicero has been the responsibility of the engineer for over 2000 years. Finally, the engineer has a loyalty to the profession and to him- or herself.

From our perspective, one cannot examine engineering ethics without considering these multiple relationships and how they interact in various situations. How does the engineer relate to the organization and the organization to its engineers? How do the organization and the larger society interact? To what extent does the organization consider itself to be responsible to the public at large? How do personal, professional, and organizational values affect moral decision making in engineering practice? Engineers must make decisions that involve (either directly or indirectly) the safety and well-being of the public. Hence, the question, To what degree should they be concerned? Do practicing engineers perceive their decisions as having an ethical component? Can the industrial engineer include this ethical component in an "objective function" or as one of the measures of effectiveness? This is not a trivial issue since most engineers have a technical education that, until very recently, has typically avoided explicit reference to these value-laden aspects of decision making. How he or she pursues them in the face of competing demands such as cost/profit, deadlines, safety, and loyalty to employer, client, public, and self is our concern.

We recognize that personal values and judgments affect the individual's engineering decisions. In addition, there is a growing body of professional codes, federal regulations, rules, and laws that provide a framework to help identify the engineer's moral obligations. In particular, the Institute of Industrial Engineers endorses the Canon of Ethics provided by the Accreditation Board for Engineering and Technology (ABET) [9].

ABET Canon of Ethics

The Fundamental Principles. Engineers uphold and advance the integrity, honor, and dignity of the engineering profession by

1. Using their knowledge and skill for the enhancement of human welfare
2. Being honest and impartial, and serving with fidelity the public, their employers, and clients
3. Striving to increase the competence and prestige of the engineering profession
4. Supporting the professional and technical societies of their disciplines

The Fundamental Canons

1. Engineers shall hold paramount the safety, health, and welfare of the public in the performance of their professional duties.
2. Engineers shall perform services only in the areas of their competence.
3. Engineers shall issue public statements in only an objective and truthful manner.
4. Engineers shall act in professional matters for each employer or client as faithful agents or trustees, and shall avoid conflicts of interest.
5. Engineers shall build their professional reputation on the merit of their services and shall not compete unfairly with others.
6. Engineers shall associate with only reputable persons or organizations.

7. Engineers shall continue their professional development throughout their careers and shall provide opportunities for the professional development of those engineers under their supervision.

For a listing of a number of other codes of ethics including the very detailed NSPE code, please see http://onlineethics.org/codes/codes.html (September 13, 2000).

AN ETHICAL FRAMEWORK

Three Core Concepts for the Individual and the Organization

In examining a series of ethical dilemmas that engineers have had to address, we have identified three core concepts that form a framework for ethical engineering decision making. Taken together, these can be used to define an ethical engineer. These principles are *competence, responsibility,* and *safety* (which we have designated as *Cicero's Creed II*). Hence, an ethical engineer is one who is (1) *competent,* (2) *responsible,* and (3) respectful of *Cicero's Creed II* [10]. Each is defined in the following sections. The first two are more obvious; the third needs some explanation.

Cicero's Creed, engineering's oldest ethic, directed engineers to place the safety of the public above all else (the first fundamental canon). We added specificity to this creed by proposing that an ethical engineer, and certainly an industrial engineer, must be knowledgeable regarding risk assessment and failure modes for a given technology or process. Further, in modern engineering practice, no matter how skilled, knowledgeable, or moral a single engineer is, he or she typically must function as part of a team and as a member of an organization. Hence, our framework must be extended to recognize both team and organizational responsibilities.

Competence

The Principle of Individual Competence. An engineer is a knowledge expert specially trained to design, test, and assess the performance characteristics of components or processes within his or her realm of expertise. To attain the status of knowledge expert with respect to a given problem area, the engineer should acquire the requisite information that is reliable, relevant, and adequate. To insufficiently do so, or to do so in a faulty manner, either knowingly or unknowingly, nullifies the position of being adequately informed. A *competent* engineer must also acknowledge what he or she does not know about a technology or process.

Within a team context, its members will bring different components of competence to the problem. The collective knowledge of the team comes closer to what is required to design the technology or system than any one could provide alone.

The Principle of Organizational Competence. An organization is *competent* if the engineers it employs collectively have the requisite knowledge to design the technology or system of interest. In a *competent organization,* each team member contributes specialized knowledge to the resolution of the problem at hand.

Note that the status of knowledge will change throughout the design process. Individual engineers expand their competence with respect to the particular issue of concern as they progress through the problem-solving process. *Organizational competence* changes with both the increased knowledge of team members and through the addition of other engineers to the project team. During the initial stages of an engineering project, we would expect that gaps exist at both the individual and organizational levels. As the project progresses, the engineers, both individually and collectively as team members, should fill in the missing knowledge gaps.

Responsibility

The Principle of Individual Responsibility. To play the role of knowledge expert in the decision-making process implies that one must make information readily available to the other participants and to take a critical attitude toward assessing decisions (including those of management) from an engineering perspective. That is, the ethical engineer must be able to develop and then effectively communicate evidence to support judgments. Equally important, the *responsible* engineer must inform the appropriate individuals about those parts of the knowledge base that he or she knows are deficient (i.e., all known knowledge gaps should be put on the table).

The Principle of Organizational Responsibility. The counterpart to the principle of *individual responsibility* is the principle of organizational (and team) responsibility. If this principle is to work on the individual level, the organization must be *responsive* to the engineer who communicates a concern. This does not mean that the organization must act on every concern raised by a responsible engineer, but it does mean that the organization must have a process for listening to and considering reported concerns. Without such an avenue, the ethical engineer may be forced to go to the worst case solution—whistleblowing.

Cicero's Creed II

Cicero's Creed II—The Individual. As noted, Cicero's original creed obligated the engineer "to insure the safety of the public." Philosophers describe this in the positive form as beneficence (i.e., doing good) but it also covers the negative aspect (do not harm, or non-malevolence). "Harm" as understood from the perspective of the individual engineer refers to his or her ability to assess the potential risks of the technology. Hence, *Cicero's Creed II: The engineer should be cognizant of, sensitive to, and strive to avoid the potential for harm and opt for doing good.* With respect to a given project, in an effort to acquire information that is reliable, relevant, and adequate, an engineer should include an assessment of the safety, risk, and possible failure mechanism for the technology or process of concern.

The organizational ethic for Cicero's Creed II involves managing technology so as not to betray the public trust. The concept of stewardship for public resources is included here, and embodies the intent of Cicero's original ethic. It is not coincidental that the Colorado School of Mines, as part of its mission statement, "has dedicated itself to the responsible stewardship of the earth and its resources" [11].

Cicero's Creed II—The Organization. A team may be required to assess the risks associated with a technology. Yet, the ethical organization assesses risk, and where potential harm may exist, makes those risks known and seeks alternatives to reduce them. By contrast, the unethical organization fails to assess risks or, having determined a serious risk, ignores its potential for harm.

ENGINEERING AS A RISK-LADEN HEURISTIC

Decision Making Under Uncertainty

The practice of engineering has been defined as a heuristic rather than an applied science. Using tradition, experience, scientific knowledge, and judgment, engineers are asked to "improve the human condition before all scientific facts are in" [12]. Broome has referred to this as the engineer's imperative [13]. Practicing engineers must address many situations that are often poorly understood. Consequently, the knowledge base from which decisions are made is often incomplete and marked by uncertainty. Certainly the last launch of the Challenger illustrates this type of situation and the consequences when the level of uncertainty and risk are not given their proper consideration.

Petroski has expanded on the view of engineering as inherently risk laden, citing four factors or "design errors" that inevitably lead to design failures [14]. Petroski looks to both the engineering profession and to the legal system to control accidents. The engineer's responsibility is the competent design of technology in order to prevent errors. In contrast, the legal system's responsibility is to police wrongdoing and mete out punishment. The design process can be conducted to prevent failures. The causes of failure include (1) conditions that approach design limit states (e.g., overloads), random or unexpected hazards that have not been considered in design (e.g., extreme weather conditions), human based errors (e.g., mistakes, carelessness), and attempts to economize in design solution or maintenance.

To this extent, Petroski, among others, urges engineers and engineering students to study past failures in order to anticipate what can happen again if proper precautions are not followed. "One of the paradoxes of engineering is that successes don't teach you very much" [15]. The Tacoma Narrows Bridge is cited as an example of this. The bridge design was based on designs of several successful bridges, yet winds destroyed the bridge a few months after it opened. The investigation of the accident revealed that, while unanticipated, there had been precedents for bridge failure under wind action. Petroski has cited 10 similar suspension bridge accidents that occurred in the nineteenth century [16].

To Petroski, computer simulation is a modern-day counterpart to the same reliance on past successes and exclusion of past failures found in designing the Tacoma Narrows Bridge. "There is clearly no guarantee of success in designing new things on the basis of past successes alone, and this is why artificial intelligence, expert systems, and other computer-based design aids whose logic follows examples of success can only have limited application," Petroski warns us [17]. This is certainly an ominous caution to the industrial engineering community, especially the growing part of it that relies on mathematical modeling and simulation.

RISK ASSESSMENT AS AN IMPORTANT IE TOOL

A Brief Overview of Risk Assessment

What can the competent, responsible industrial engineer do about risk? Since engineering is never risk free, we propose that part of the IE's toolkit should be the ability to assess risk. These risk analysis techniques range from qualitative hazard analysis and failure modes and effects analysis (FMEA) to probabilistic risk assessment (PRA) including fault tree analysis (FTW). A comprehensive risk analysis for a complex system might utilize the full range of techniques, with the results from the qualitative stages becoming the input for the more quantitative stages [18]. Bell has provided definitions of some of the basic terms in risk assessment and analysis as well as an overview of some of the techniques [19]. Voland provides an overview of the qualitative techniques illustrated with a number of short case studies [20].

A formal hazard analysis is a top-down approach in which all potentially unsafe conditions or events posed by the environment, machine interfaces, human error, and so on are enumerated and the frequency and severity of each hazard estimated. As used by NASA, the potential sources of these conditions are also identified, and a procedure for their mitigation and/or acceptance of the risk is explicitly provided [21]. That is, identified hazards and their causes are analyzed to find ways to eliminate (remove) or control the hazard (design change, safety or warning devices, procedural change, operating constraint). Any hazard that cannot feasibly be eliminated or controlled is explicitly termed an "accepted risk" [22]. While hazard analysis can be used early in the design phase in order to identify potential hazards [23], the methodology is also recommended as a means of further analyzing the failure modes identified in FMEA process [24].

The FMEA employs a bottom-up approach. Starting at the component level for each subsystem, the analyst determines how the device or part might fail and what would be the effects and consequences of such a failure on the component and all other interfacing, interacting components. The consequences of each identified failure mode are then classified according to its severity. In the case of the space shuttle, failure modes that could lead to the loss of crew and/or vehicle have been classified as Criticality-1 (CRIT-1) or 1-R if the item of concern is redundant. CRIT-1 items are then collected on a critical items list (CIL), which serves as a management tool to focus attention on the mitigation or control of the failure mode through redesign, use of redundant components, special inspections, or tests [25]. Each item on the critical items list requires a formal, written rationale for its retention on the shuttle. In this manner, engineers and managers were required to explicitly waive NASA policy against flying with such items present prior to each shuttle launch [26]. For reasons that are discussed in detail elsewhere, such a system failed to prevent the loss of the Challenger [27].

Recently, there has been considerable interest in using reliability analysis to determine the probability of failure. One such set of techniques is probabilistic risk assessment (PRA), also a top-down technique in which the possible failure mode of the complete system is identified first, and the possible ways that the failure might occur are enumerated. A fault tree is developed by tracing out and analyzing the contributory faults, or chains of faults for each event, until the basic fault (e.g., single component failure or human error) is reached. Probabilities are then assigned to the various basic faults or errors. This enables probabilities for the various failures to be estimated, and their relative contribution to total risk assessed. In theory, the failure modes with the highest probabilities should be addressed first. When used correctly, PRA yields a measure of risk from a chain of events and an estimate of uncertainty [28]. Fault tree analysis was first developed by Bell Laboratories and later used extensively by NASA [29].

Elisabeth Paté-Cornell's Contribution to PRA

The most prolific and creative use of PRA models has been by M. Elisabeth Paté-Cornell (professor and chair, Department of Industrial Engineering and Engineering Management) and her colleagues at Stanford. They have used this technique retrospectively and prospectively to both estimate risk and to identify the organizational factors that were the root contributors to the failure of critical engineering systems. For example, by introducing organizational aspects into probabilistic risk assessment of several offshore oil platform failures, Paté-Cornell was able to derive coarse estimates of the benefits of certain organizational improvements, and resultant reliability gains. In the case of jacket-type offshore platforms, the cost of these gains are two orders of magnitude less than the cost of achieving the same result through structural changes [30].

Paté-Cornell and Paul Fischbeck used PRA to model the failure risk associated with each of the 25,000 thermal tiles on the space shuttle. Their model is then used to set priorities for maintenance of the tiles. Their paper provides an outstanding case study in the use of PRA models [31]. In a second paper, they show how their PRA model was used as a management tool to identify the root-cause organizational factors of the various failure modes for the shuttle's thermal protection system [32].

A later paper with Murphy codifies her earlier work into the SAM approach (system-action-management) to more formally link the probabilities of system failures to human and management factors. Here they also provide insights into the importance of informal reward systems, the difficulties in communicating uncertainties, the problems of managing resource constraints, and the safety implications of the shortcuts taken to deal with these factors [33]. In short, they demonstrate how such factors as we have noted previously, if uncorrected or unchecked, lead to ethical dilemmas and serious consequences for the involved parties.

In recent work, Paté-Cornell and Dillon are using PRA to analyze NASA's "faster, better, cheaper" (FBC) mode of operation of its unmanned space program. If FBC is to be successful, then explicit tradeoffs among risks, costs, and schedules will have to be made. This requires NASA managers to be cognizant of the risks involved. Paté-Cornell and Dillon propose that PRA can be a valuable tool in this approach. They also propose ways that PRA can be used to do this and provide examples and an overview [34, 35].

SUMMARY

We have tried to show how the pressures of the engineering workplace combined with the conflicting loyalties of the professional engineer can lead to situations that can be termed ethical dilemmas. We have done this by citing some examples. To help reduce potential ethical dilemmas, we have provided a framework of behavior for the ethical engineer. In short, this framework that we developed with two colleagues—Rose Pinkus and Norman Hummon—requires the engineer to be competent, responsible, and to understand and minimize the risk involved in his or her engineering endeavors. To us, this last point is especially relevant. In fact, we propose that the modern industrial engineer must understand risk assessment and utilize probabilistic risk assessment where applicable and warranted.

Engineering Ethics on the Web

For those readers who wish to pursue this subject further, there is a rapidly developing body of literature including cases on engineering ethics and much of this can be found on the World Wide Web. Some examples follow.

- The National Institute for Engineering Ethics (www.niee.org/index.htm) created by the National Society of Professional Engineers (NSPE) in 1988 and now an independent not-for-profit educational corporation. The mission of NIEE, like that of its predecessor, is to provide opportunities for ethics education and to promote the understanding and application of ethical processes within the engineering profession and with the public.
- The Murdough Center (http://www.coe.ttu.edu/murdough/default.htm), College of Engineering, Texas Tech, has, as a primary goal, to increase the awareness of an engineer's professional and ethical responsibilities by encouraging and promoting professional programs and activities emphasizing engineering ethics. The center conducts symposia, workshops, and seminars throughout the state and nation for industry, professional societies, and academic institutions. With the ratification of the North American Free Trade Agreement (NAFTA), the center has begun working with engineers in Canada and Mexico to develop a basic understanding and appreciation of mutual interests in principles of conduct and ethics as they relate to professional engineering practice.

  Under funding from NSF, Professors Michael J. Rabins (Department of Mechanical Engineering) and Professor Ed Harris (Department of Philosophy) developed and tested 11 student handouts and instructor's guides in 11 different courses in the agricultural, chemical, civil, and mechanical engineering departments at Texas A&M University. A number of these cases are available for use by students at http://lowery.tamu.edu/ethics/.
- The WWW Ethics Center for Engineering and Science was established in the fall of 1995 under a grant from the National Science Foundation. Its mission is to provide engineers, scientists, and science and engineering students with resources useful for understanding and addressing ethically significant problems that arise in their work life. The center is also intended to serve teachers of engineering and science students who want to include discussion of ethical problems closely related to technical subjects as a part of science and engineering courses, or in free-standing subjects in professional ethics or in research ethics for

such students. The Ethics Center and its mirror site are located on the campus of Case Western Reserve University (CWRU) (http://onlineethics.org/index.html).

- Another very valuable and well-organized site is the Web Clearinghouse for Engineering and Computing Ethics, Division of Multidisciplinary Studies, North Carolina State University, which is maintained by Joseph Herkert and cosponsored by Resource Guides Committee of the National Institute for Engineering Ethics (http://www4.ncsu.edu/unity/users/j/jherkert/ethicind.html/). A helpful, overview paper is also available [36].

Three Helpful Books

Finally, we would refer the interested reader to three other particularly valuable books. The first, by Harris, Pritchard, and Rabins, *Engineering Ethics: Concepts and Cases,* may be the most widely used engineering ethics text; it includes a number of very good cases as well as a process for resolving ethical dilemmas [37]. Johnson's *Ethical Issues in Engineering* places professional ethics issues in context [38]. She has separate sections dealing with the various loyalties of the professional engineer. For those interested in ethics as applied to mathematical modeling, Wallace has edited a collection of very provocative papers that resulted from a conference held at RPI in 1989 [39]. In particular, such issues as the proper relationship between the model builder and the model user, the extent to which the model builders assume professional responsibility for the results of their models, and the responsibility of the model builders to the public (as opposed to the client) are addressed. It should be read by anyone who develops models for other than recreational purposes.

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BIOGRAPHIES

Larry J. Shuman is Associate Dean for Academic Affairs, School of Engineering, University of Pittsburgh and professor of Industrial Engineering. His current interests are improving the engineering educational experience, and studying the ethical behavior of engineers and engineering managers. He is a coauthor of *Engineering Ethics: Balancing Cost Schedule and Risk—Lessons Learned from the Space Shuttle* (Cambridge University Press, 1997). Prior to that, Dr. Shuman in collaboration with Dr. Wolfe worked extensively in the field of health care delivery. Dr. Shuman has been principal or coprincipal investigator on over 20 sponsored research projects funded from such government agencies and foundations as the National Science Foundation and the U.S. Department of Health and Human Services. He holds a Ph.D. in Operations Research from the Johns Hopkins University, and a B.S.E.E. from the University of Cincinnati. He will be the academic dean for the "Semester at Sea" for the spring 2002 semester.

Harvey Wolfe has been a professor in the Department of Industrial Engineering at the University of Pittsburgh since 1972 and department chair since 1985. He received his Ph.D. in Operations Research from the Johns Hopkins University in 1964. He is a Fellow of the Institute of Industrial Engineers and serves as member at large of the Professional Enhancement Board of the Institute of Industrial Engineers. He is currently president of the Council of Industrial Engineering Academic Department Heads. He is serving his second six-year term as an ABET evaluator. After many years working in the area of applying operations research methods to the health field, he is now active in the development of models for assessing engineering education. He is a coauthor of *Engineering Ethics: Balancing Cost Schedule and Risk—Lessons Learned from the Space Shuttle* (Cambridge University Press, 1997).

CHAPTER 2.8

CASE STUDY: PRODUCTIVITY IMPROVEMENT THROUGH EMPLOYEE PARTICIPATION

Lennart Gustavsson
Productivity Management
Frölunda, Sweden

The improvement of productivity is the primary assignment of industrial engineers. Traditionally, industrial engineers have performed the entire task of improving productivity themselves. They have simultaneously developed effective systems and techniques for the industrial engineering effort. The results of these developments have been implemented in cooperation with affected personnel. Nowadays, productivity development work (in this case study referred to as *development*) has become the concern of all the employees in an organization and is therefore best performed in logically organized work teams. The role of industrial engineers has expanded, from simply executing to supporting and coordinating, although they continue to provide and develop efficient systems and techniques. Through the active participation of all employees, the continuous development of many productivity improvements is accomplished. These improvements are implemented very quickly by their respective work teams. Simultaneously, a very good work environment is created for cooperation concerning development issues. Productivity development through active participation of all employees can be applied to all types of businesses and organizations, and the following case study describes and illustrates how this has been accomplished in a manufacturing company.

BACKGROUND AND ANALYSIS OF THE INITIAL SITUATION

Elektrotryck AB produces printed circuit boards for the electronics industry. The headquarters and one production unit are located in Ekerö (just west of Stockholm, Sweden), and a second production unit is located in Timrå (approximately 350 kilometers north of Stockholm). The company's annual business revenue was 175 million Swedish kronor (approximately U.S.$22.5 million). Elektrotryck has around 160 employees, divided equally between Ekerö and Timrå.

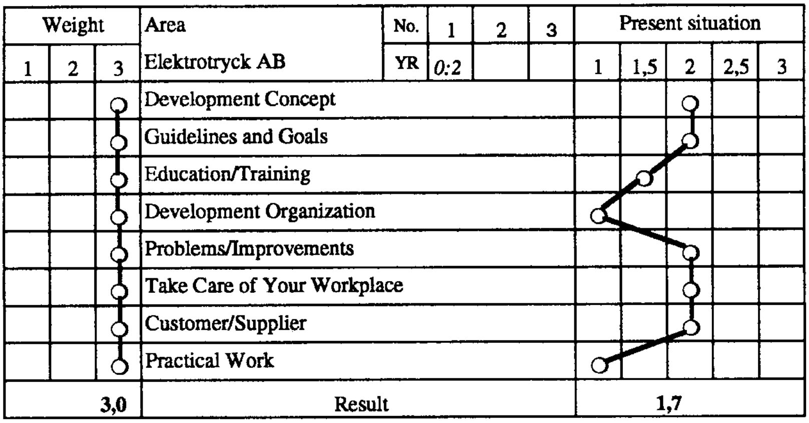
In the beginning of the first development, company management discussed the possibility of increasing production volume within the framework of existing production resources. During that year, the company management initiated a development project to increase overall productivity, which would include quality, delivery reliability, finance, personnel development, and work environment and in which all employees would actively participate.

In the initial stage, it is important to establish how far the development has proceeded (the technical development status). Thereby, the development process can be adapted so that a relatively greater effort can be made in less developed areas. At the end of the start-up phase, it is just as important to determine how far the actual development has proceeded in relation to the plan. During a two-day seminar on productivity improvement through employee participation for function heads and personnel representatives, analysis of the initial situation was carried out. This analysis consists of eight primary factors, each of which includes about five subfactors. Aided by definitions and through discussions, the team reached a consensus re-garding a common evaluation per factor for the entire company. Important arguments were noted. The team accomplished its analysis in about four hours. A summary of Elektrotryck's initial situation is shown in Fig. 2.8.1. As is evident from this figure, all initial evaluation factors were considered very important (value 3.0) and that the technical development had just begun (value 1.7). The company's technical development status was discussed during the basic training of the employees and was considered during the continued development work.

GOALS AND SCOPE

The goals for productivity improvement through employee participation are as follows:

- To introduce and continuously apply appropriate development concepts, procedures, and methods in order to substantially improve Elektrotryck's ability to meet future increases in demands on quality, delivery ability, finance, personnel development, and work environment



Weight
3 Very important. Great significance.
2 Less important. Some significance.
1 Not important. No significance.

Present situation
3 Development completed. Application to full extent.
2 Development in progress. Application to a certain extent.
1 Development not started. No application.

FIGURE 2.8.1 Technical development status in the start-up phase.

CASE STUDY: PRODUCTIVITY IMPROVEMENT THROUGH EMPLOYEE PARTICIPATION

- To increase the business volume by approximately 30 percent within the framework of existing production resources and personnel during the next two-year period
- To complete the start-up work within approximately eight working months

The development work encompasses all operations in Ekerö and Timrå, which are units of about the same size within Elektrotryck (Fig. 2.8.2).

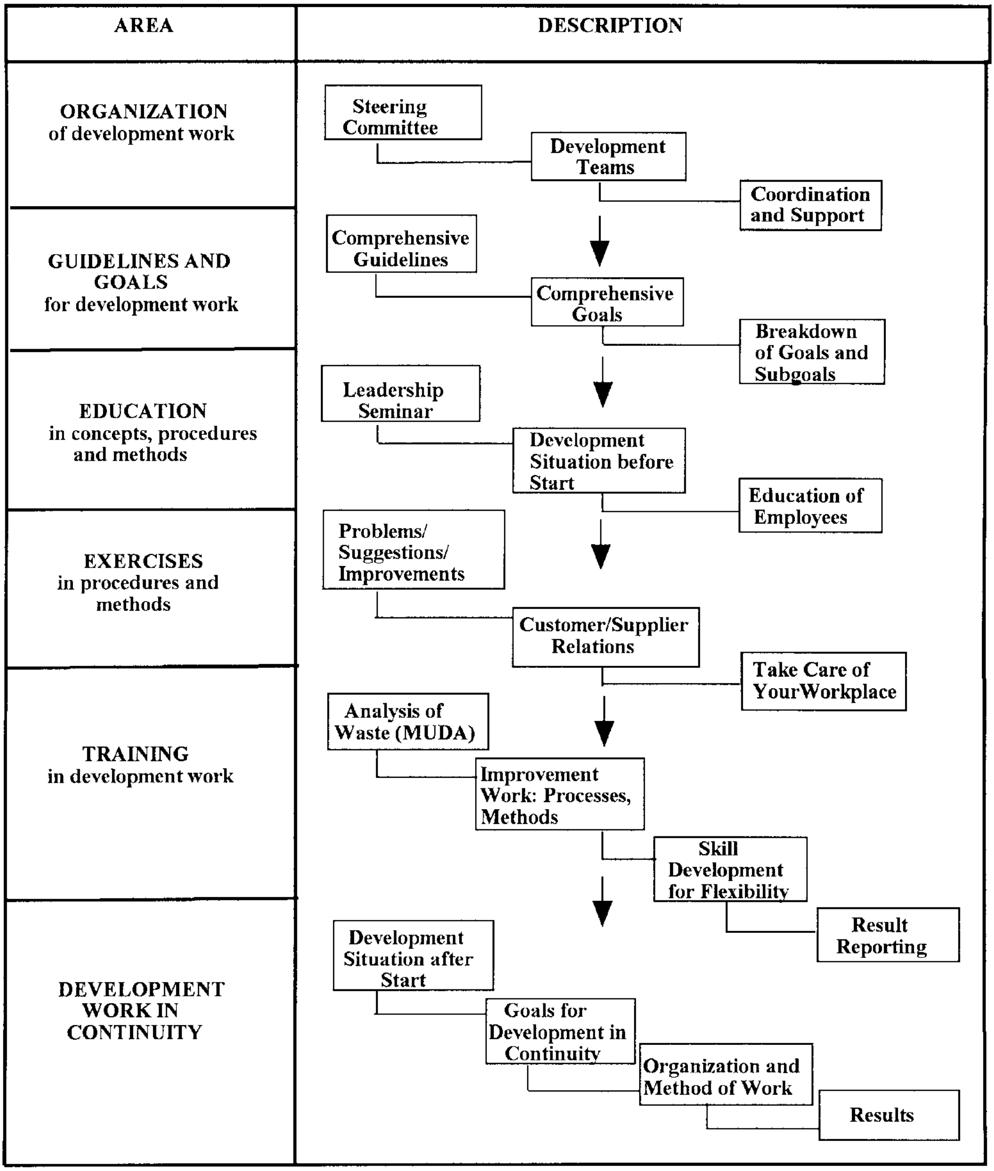

AREA
DESCRIPTION
ORGANIZATION of development work
GUIDELINES AND GOALS for development work
EDUCATION in concepts, procedures and methods
EXERCISES in procedures and methods
TRAINING in development work
DEVELOPMENT WORK IN CONTINUITY
Steering Committee
Development Teams
Coordination and Support
Comprehensive Guidelines
Comprehensive Goals
Breakdown of Goals and Subgoals
Leadership Seminar
Development Situation before Start
Education of Employees
Problems/ Suggestions/ Improvements
Customer/Supplier Relations
Take Care of Your Workplace
Analysis of Waste (MUDA)
Improvement Work: Processes, Methods
Skill Development for Flexibility
Result Reporting
Development Situation after Start
Goals for Development in Continuity
Organization and Method of Work
Results

FIGURE 2.8.2 Scope of development work.

ORGANIZATION OF THE DEVELOPMENT WORK

Steering Committee

A steering committee was formed as the highest decision-making and reporting authority regarding productivity development within Elektrotryck. It consists of the managing director, the marketing director, the technical director, the production managers from the Ekerö and Timrå units, the finance director, two personnel representatives, the development coordinator, and, during the start-up phase, a consultant.

The steering committee and its members have the following assignments:

- To establish comprehensive guidelines and goals for the development work
- To efficiently organize the development work
- To make comprehensive decisions concerning the development work
- To be informed of and evaluate progress and results
- To daily take an interest and encourage employees in the development work

The steering committee meets regularly once a month to discuss the following issues:

- Progress of the development work
- Issues requiring decisions by the steering committee
- Planning of forthcoming development work
- Information about the development work to all employees
- Reports from one or more development teams

A steering committee meeting takes approximately three hours, during which one development team presents a half-hour report. Each member of the steering committee also visits for half an hour with different development teams two or three times a week to take an active part in respective teams' improvement work.

Support teams have been formed for the following organizational units:

- Production in Timrå
- Production in Ekerö
- Administration for Elektrotryck in Ekerö

Each support team consists of management personnel, the unit's personnel representative, and the development coordinator. The support team meets regularly once a month and has assignments within its unit similar to the steering committee's assignments within the company.

Development Teams

Within each logical work area, a development team was formed incorporating all the employees of the area. Each development team has the following assignments:

- To identify problems and suggest/implement improvements
- To break down the comprehensive goals into goals for the development team and implement improvements that satisfy the goals
- To implement and continuously apply the concepts "Take care of your workplace" and "We are all each other's customers"
- To plan and implement skill development for the development team's employees

- To compile development results and report to the steering committee through the respective support team
- To encourage the development team's employees in the development work

Each development team meets, in conjunction with the shift change, three to four times a week in its meeting area. At that time, goals, problems, suggestions, and improvements are discussed (workplace and area improvements, customer and supplier problems, etc.). The development team distributes assignments for improvement and implementation of suggestions to team members, to be completed outside of the team meetings.

The development team's goals and achieved results are visualized on a whiteboard, which is continuously updated. Each Monday the development team compiles the preceding week's results and plans the development work for the coming week. In total, approximately 15 minutes per day per employee are allocated to productivity development work.

Coordination and Support

One person has been appointed to coordinate and support the productivity development work. The coordinator has the following assignments:

- To develop a comprehensive plan for the productivity development work
- To provide necessary development concepts, procedures, and techniques for the development work
- To establish and maintain an effective development organization
- To direct the development of comprehensive guidelines and goals
- To plan and coordinate training and exercises in development work
- To coordinate the development work between the development teams and provide special know-how
- To coordinate the follow-up, reporting, and information concerning results

The coordinator participates on the steering committee as the presenter of reports. Also, he or she participates in the meetings of the support teams and assists in the development work as needed. Coordination and support of the productivity development work within Elektrotryck is a full-time position.

GUIDELINES AND GOALS FOR THE DEVELOPMENT WORK

Guidelines provide the direction of the development of the operation (e.g., "to satisfy the customer's demand for quality"). *Goals* indicate how far the guideline can be realized during a given time period (e.g., "to decrease claims by 40 percent during the next year"). (See Fig. 2.8.3.)

Comprehensive guidelines and goals are the foundation for all development activities in the company. Each of the development teams sets up its own goals based on the comprehensive goals. The development teams begin their improvement work within their own area (with their own defects, workplace order, equipment inspection, waste of consumption materials, etc.). Over time, ideas for more extensive improvements will emerge. Projects may evolve that require the involvement of several development teams, possibly with the assistance of specialists. The company's development work with respect to new processes and acquisitions of facilities and machinery through investments is managed in the same way. Total development efforts are combined to achieve the results that correspond to the comprehensive goals of the operation, which are displayed in Fig. 2.8.4.

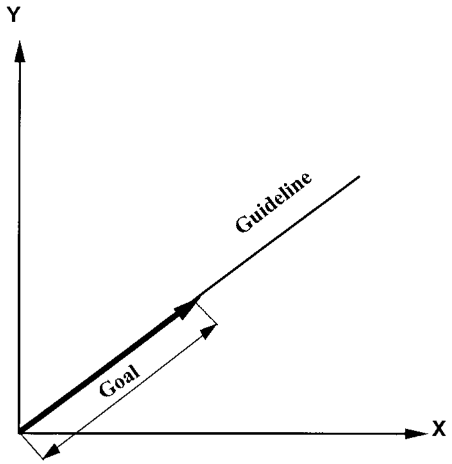

Y
Guideline
Goal
X

FIGURE 2.8.3 Sketch in principle: goal/guideline.

All businesses have comprehensive guidelines and goals. Some of these are directly applicable to the work of developing productivity, while others must be supplemented or some new ones prepared. Current guidelines and goals can be difficult to comprehend for people who have not participated in their preparation. Explanations will help everyone understand the meaning. Supplementing and further developing of current guidelines and goals for use in the productivity development work will be required in most cases. Guidelines and goals are divided into the following sections:

- Quality
- Delivery
- Finance
- Personnel
- Environment

Figure 2.8.5 shows in principle how comprehensive guidelines and goals are prepared and how these goals are broken down into subgoals for the respective development team.

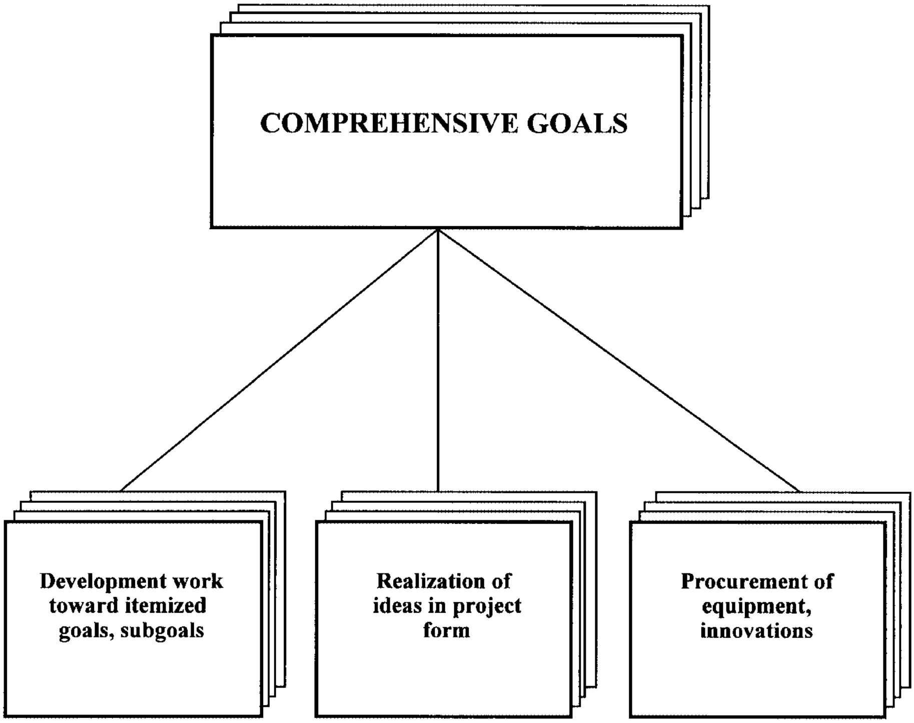

COMPREHENSIVE GOALS
Development work toward itemized goals, subgoals
Realization of ideas in project form
Procurement of equipment, innovations

FIGURE 2.8.4 Overview of development efforts to achieve comprehensive goals.

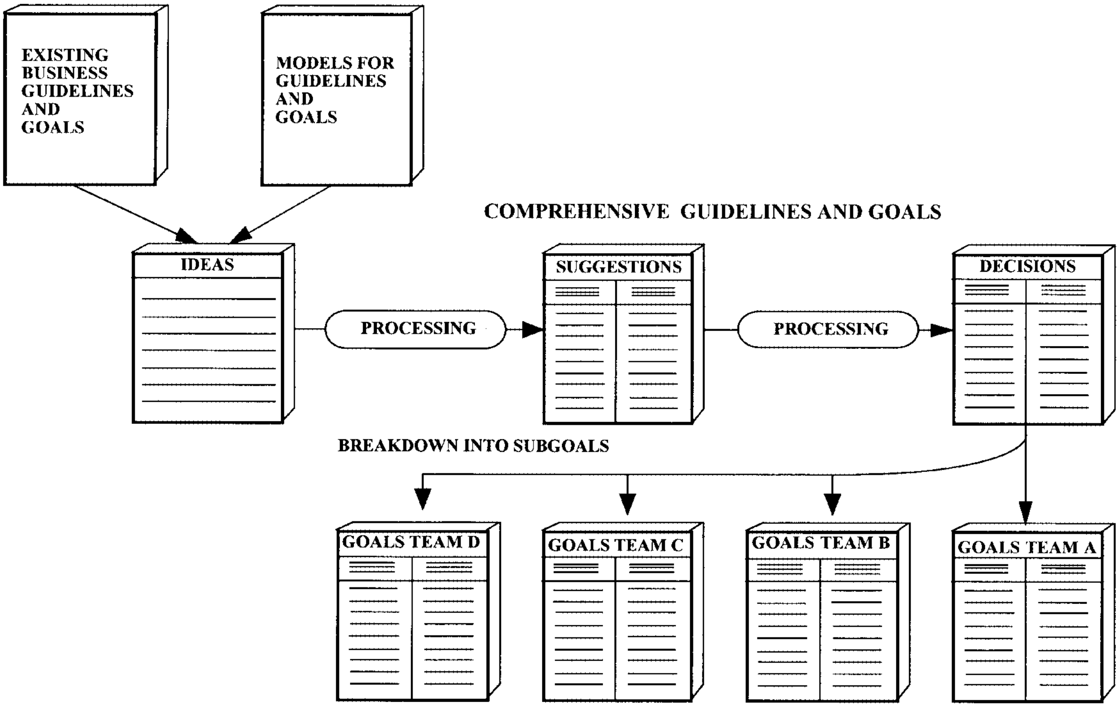

EXISTING BUSINESS GUIDELINES AND GOALS
MODELS FOR GUIDELINES AND GOALS
COMPREHENSIVE GUIDELINES AND GOALS
IDEAS
PROCESSING
SUGGESTIONS
PROCESSING
DECISIONS
BREAKDOWN INTO SUBGOALS
GOALS TEAM D
GOALS TEAM C
GOALS TEAM B
GOALS TEAM A

FIGURE 2.8.5 Establishing guidelines and goals for productivity improvement.

Comprehensive Guidelines and Goals

The steering committee assigned eight people from the management team, including personnel representatives, to establish comprehensive guidelines and goals. At the first meeting this team studied the company's current guidelines and compared them to models made available by the consultant. During a brainstorming session, all ideas and arguments were noted. The time consumption for this session, as well as the one following, was approximately three hours.

For the subsequent meeting, the coordinator prepared a summary of ideas and arguments as suggestions. During the following meeting the team worked the suggestions into a recommendation, which was then submitted to the steering committee for a decision. The committee then followed the comprehensive guidelines to prepare the comprehensive goals for the development activities.

Each year, the comprehensive guidelines were revised and comprehensive goals prepared by the steering committee mandated by company management. Examples of Elektrotryck's comprehensive policies and goals are shown in Figs. 2.8.6, 2.8.7, and 2.8.8.

Breakdown of Goals, Subgoals

Some of the comprehensive goals were so universal that they could be applied by all of the development teams (e.g., "each development team has as its goal to implement an average of five improvements during the following year per team member"). Most of the comprehensive goals, however, had to be broken down and transformed in order to suit the respective devel-

GUIDELINES FOR DEVELOPMENT

QUALITY

Guidelines	Explanations and Clarifications
We shall be one of the leading printed circuit board manufacturers in the world.	* By satisfying our customers' demand for total quality, which means: • products free from defects • delivery at agreed upon time • constantly improved technical processes • constantly shorter delivery times • constantly lower total cost for the customer. * By paying attention to our customers' desire for: • service • flexibility • improvements • good cooperative practices and relations.
We shall continously strive to improve our total quality.	* By everyone's responsibility for the quality of his or her own work, which means: • to know and understand the quality demands of the customers • to be able to perform work processes according to provided instructions • leave products free from defects for the next process • take in information about defects • learn from mistakes

FIGURE 2.8.6 Comprehensive guidelines for quality.

opment team. For example, "to decrease the number of claims by 50 percent during the following year" did not provide a direct foundation for establishing subgoals for the various development teams.

Figures 2.8.9 to 2.8.12 show how the company's goals for claims were broken down into subgoals for the marketing development team. The development team for the company management analyzed the 137 claims that were received during the initial year and came up with the distribution shown in Fig. 2.8.9.

The development team for marketing analyzed its 82 claims for the initial year, which produced the distribution shown in Fig. 2.8.10. The comprehensive goal for the following year was to decrease the number of claims by 50 percent (Fig. 2.8.11). Therefore, at the initial year's turnover rate, the goal for the following year was set at 41 claims. Because the turnover was expected to rise by approximately 30 percent during the following year, the goal was set at 53 claims, with the distribution as shown in Fig. 2.8.12.

QUALITY	
GOALS	**Explanations and Clarifications**
We shall be considered one of the best in the industry, year **3** **4**	**We shall deliver products and services to our customers:** **- without defects** **- in the shortest time** **- without deviations from agreed upon time** **- constantly lower total cost for the customer**

FIGURE 2.8.7 Comprehensive goals for quality.

Each development team established its own goals based on the comprehensive goals for quality, delivery, finance, personnel, and environment—a total of approximately 15 per team. The goals of the development teams are kept in a file folder at each team's meeting place. All development teams regularly compare results against the goals and report to their support team and the steering committee.

TRAINING IN CONCEPTS, PROCEDURES, AND METHODS

Productivity development through employee participation relies on rational thinking, standard development techniques, and common sense. In order for everyone at Elektrotryck to be consistent in productivity development and consequently achieve satisfactory results, everyone received similar training in development concepts, development procedures, and development methods. The training covered the following topics:

1. *Development concepts*
   - The way in which to think
2. *Development procedures*
   - Organization of the development work
   - Guidelines and goals for the development work
   - Problems, suggestions, improvements
   - Customer/supplier relations
   - Improvements of workplaces and work areas
   - Reporting of results
3. *Development methods*
   - "Seven tools" and others

The training consisted of the following:

QUALITY		
GOALS	**Explanations and Clarifications**	
Our comprehensive quality goal for the following year is:		
• To reduce number of claims by: 50%	Number of shipments, initial year:	3802
	Number of claims, initial year:	137
	Percent claims, initial year:	3,6
	Number of shipments, following year:	4960
	Number of claims, following year:	89
	Percent claims, following year:	1,8
• To reduce the value of rejected claims and internal rejections by: 20%	Gross revenue, initial year:	US$ 20,4 M
	Rejections total, initial year:	US$ 1,1 M
	Percent rejections, initial year:	5,4
	Gross revenue, following year:	US$ 22,5 M
	Rejections total, following year:	US$ 1,0 M
	Percent rejections, following year:	4,3

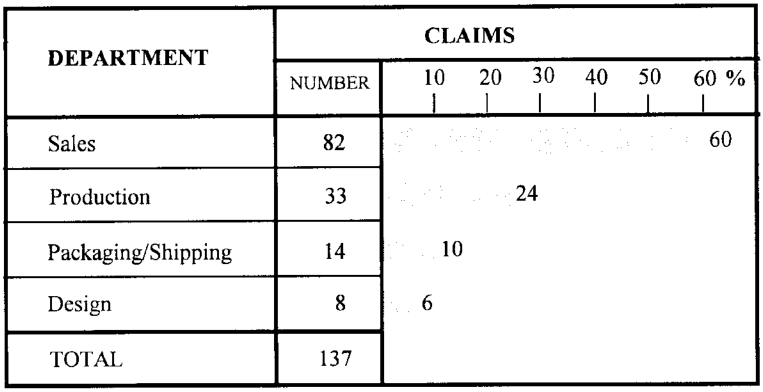
FIGURE 2.8.8 Comprehensive goals for claims and rejections.

- Theoretical lessons
- Exercises as team projects
- Training in practical development work

In all training, the so-called cascade model was applied, meaning that each leader trained his or her own coworkers and the training could therefore become a natural part of everyday work. (See Fig. 2.8.13.) The consultants trained Elektrotryck's steering committee.

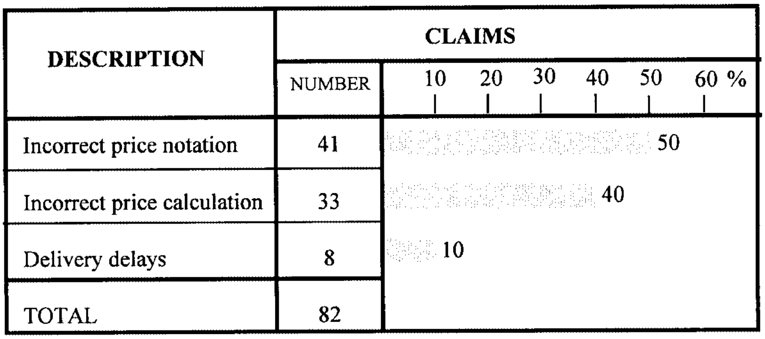
The training at Elektrotryck covered the following:

- Basic training in productivity development through employee participation
- Exercises and training in practical development work
- Training in development methods



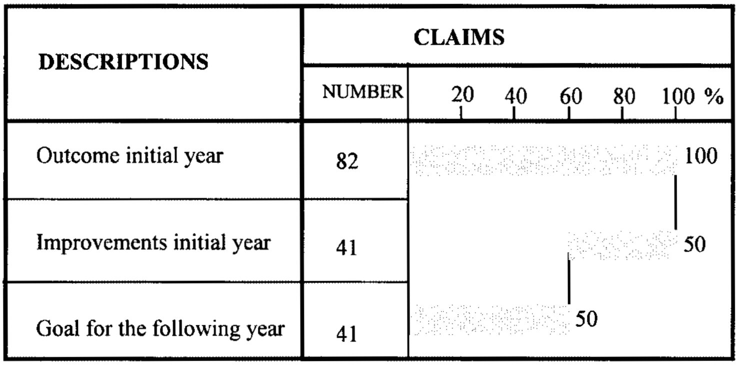
DEPARTMENT	CLAIMS	
	NUMBER	10 20 30 40 50 60 %
Sales	82	60
Production	33	24
Packaging/Shipping	14	10
Design	8	6
TOTAL	137	

FIGURE 2.8.9 The company's claims, initial year.



DESCRIPTION	CLAIMS	
	NUMBER	10 20 30 40 50 60 %
Incorrect price notation	41	50
Incorrect price calculation	33	40
Delivery delays	8	10
TOTAL	82	

FIGURE 2.8.10 The marketing group's claims, initial year.



DESCRIPTIONS	CLAIMS	
	NUMBER	20 40 60 80 100 %
Outcome initial year	82	100
Improvements initial year	41	50
Goal for the following year	41	50

FIGURE 2.8.11 The marketing group's goal for claims at the initial year's turnover rate.

DESCRIPTION	**CLAIMS**	
	NUMBER	10 20 30 40 50 60 %
Incorrect price notation	27	50
Incorrect price calculation	21	40
Delivery delays	5	10
TOTAL	53	

FIGURE 2.8.12 The marketing group's goal for claims, year following initial year.

The following pages will describe the content of and time allocation for the training and show examples of the management of the training. Training material consisted of overhead images and exercises. Binders were compiled at both Timrå and Ekerö to make the material uniform, readily accessible, and easily copied in smaller quantities. Course participants received only exercise material. A binder with the course material was distributed to each development team.

Figures 2.8.14 and 2.8.15 show summaries of basic training for management personnel and employees, respectively.

Development Concept

To pursue industrial engineering development work in which everyone in the company actively participates is vastly different from earlier working models in which industrial engineering specialists carried out the majority of the development work.

New ways of thinking and a new management style are required for everyone's involvement. These include an attitude toward progress that seeks continuous improvement of what

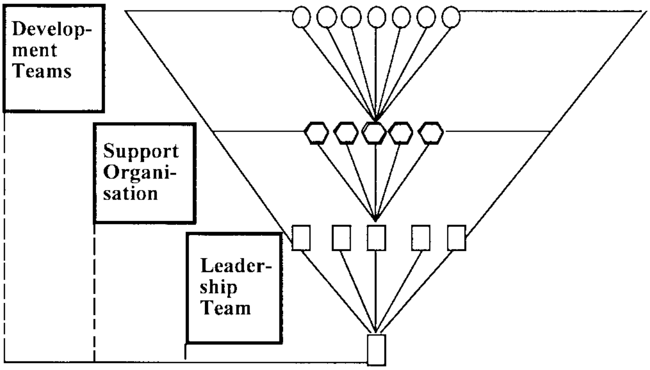


FIGURE 2.8.13 The cascade model.

CASE STUDY: PRODUCTIVITY IMPROVEMENT THROUGH EMPLOYEE PARTICIPATION

No.	DESCRIPTION	Time, Days
1	INTRODUCTORY PRESENTATION.	1/2
2	START-UP. Program review.	1/4
3	SEMINAR PROGRAM. Presentation of schedule.	1/4
4	DEVELOPMENT CONCEPT. The way to think.	3*
5	ANALYSIS OF PRESENT SITUATION. Current conditions.	2*
6	GUIDELINES AND GOALS. Comprehensive for entire business and broken down to apply to units and groups.	2*
7	EDUCATION AND TRAINING.	1
8	DEVELOPMENT ORGANIZATION. Management, coordination, development teams and control system.	1
9	VALUE ANALYSIS. Analysis of resources for elimination of non-value-added items.	2*
10	PROBLEM SOLVING METHODOLOGY. Procedures for improvement work aided by P-D-C-A.	2*
11	CUSTOMER/SUPPLIER RELATIONS. Method of work to satisfy external and internal customers.	1
12	IMPROVEMENT OF WORKPLACES AND WORK AREAS. Procedure in five steps.	1
13	TRAINING IN DEVELOPMENT WORK. Review of one week's practical development work.	1
14	RESULT STATEMENT. Reporting of results.	1
15	DEVELOPMENT WORK IN CONTINUITY. Review and scheduling.	1
16	CONCLUDING REMARKS.	1/2
* including group discussions	Total:	20

FIGURE 2.8.14 Content and time allocation for the basic training of management personnel, leadership seminar.

exists, a conviction that we can do better today than yesterday and better tomorrow than today, and the constant application of new theories and techniques.

- The customer comes first.

  Customer demands and satisfaction are the motivating force.
- Everyone participates actively in the improvement process.

  Everyone is a problem solver. Managers are setting an example.

No.	DESCRIPTION	Time, Days	Instructor
1	BACKGROUND. Start-up of development work.	1/4	H.Floren (HR-Mgr)
2	DEVELOPMENT CONCEPT. The way to think.	2	A.Björsell (Mgr Dir)
3	ANALYSIS OF PRESENT SITUATION. Current conditions.	1	L.Åström (Supervisor)
4	GUIDELINES AND GOALS. Comprehensive guidelines and goals, breakdown of goals in subgoals.	1	A.Björsell
5	EDUCATION AND TRAINING. DEVELOPMENT ORGANIZATION.	1	H.Floren
6	VALUE ANALYSIS, PROBLEM SOLVING METHODOLOGY.	2	L.Åström
7	CUSTOMER/SUPPLIER RELATIONS. IMPROVEMENT OF WORKPLACES AND WORK AREAS.	1	-”-
8	TRAINING IN DEVELOPMENT WORK. Review of practical development work	1	-”-
9	DEVELOPMENT IN CONTINUITY.	1/2	H.Floren
10	CONCLUDING REMARKS.	1/4	A.Björsell
	Total:	10	

FIGURE 2.8.15 Content, time allocation, and instructors for the basic training of employees.

- Everyone is trained in concepts, procedures, and methods.
  Trained employees are committed employees.
- Development goals and results are established and reported.
  This creates interest in the development work.
- Improvement is focused on quality, delivery, finance, personnel, and environment.
  Quality is prioritized. This leads to, among other things, lower costs.
- Problems are seen as opportunities.
  Problems are solved at the workplace. Improvements are implemented quickly and systematically applying the Plan-Do-Check-Act (P-D-C-A) procedure.
- Recognition is given for good development results.
- Productivity is, above all, a personal attitude.

Development systems will be discussed under the next two major headings, Exercises in Procedures and Training in Development Work.

CASE STUDY: PRODUCTIVITY IMPROVEMENT THROUGH EMPLOYEE PARTICIPATION

Development Tools

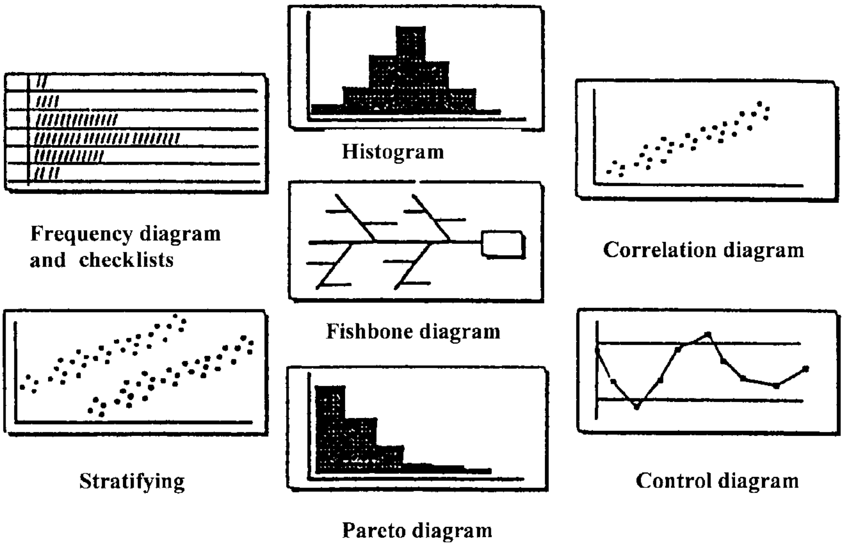
In all industrial engineering development work, methods are required for identifying and analyzing problems, creating and implementing solutions, and following up results. Therefore, in productivity development through employee participation, each development team must be thoroughly grounded in the most useful methods, which include the seven tools shown in Fig. 2.8.16 (in addition to brainstorming, process diagrams, etc.).

Each development team plans a four-hour training session in development methods for its members. The team leader or the coordinator conducts the training. Whenever the development team requires a different method in order to properly carry out its development work, the coordinator is contacted, and he or she arranges for the correct skill to be provided for the team to ensure that the quality of the development work will not be compromised.

Skill development will be discussed under the next two major headings, Exercises in Procedures and Training in Development Work.

EXERCISES IN PROCEDURES

It took about four working months to analyze the current situation, implement the leadership seminar, and establish guidelines and goals, development organization and training concepts, and procedures and methods. Thereafter, the development work was successively initiated in the 28 development teams. At the outset, the team separated the comprehensive goals into subgoals, which were kept in a binder at the team's meeting place. The team selected those goals it wanted to report on and posted them on the team's whiteboard. Simultaneously, the team practiced the development procedures concerning problems, suggestions, improvements, customer and supplier relations, and improvements in the workplace during approximately one working month.


Frequency diagram and checklists

Histogram

Correlation diagram

Fishbone diagram

Stratifying

Control diagram

Pareto diagram

FIGURE 2.8.16 The seven tools.

During the same period, at Timrå and Ekerö, management carried out a one-week training session in practical improvement work under the supervision of consultants. This allowed each manager to later carry out a similar training program for his or her development team. All development teams had completed their training week after about three working months. The master schedule for productivity development within Elektrotryck is shown in Fig. 2.8.17.

Problems/Suggestions/Improvements

A general goal for all development teams was to implement an average of five improvements per team member per year. Every team member was requested to submit problems within his or her own area. Throughout the company, a standard form was used based on the Plan-Do-Check-Act (P-D-C-A) principle.

At a team meeting, the presenter introduced his or her problem. The development team discussed suggestions for a solution. Team members were assigned to test the solution and implement the improvement. Target dates were set for the completion of the development work. Progress and results were continuously reported at the team meetings and the work status logged. Once an improvement had been implemented, the development team assessed and documented the results. An example of the processing of a problem is shown in Fig. 2.8.18.

A total of 1994 problems were addressed by the development teams during the following year, and 1440 improvements were implemented that same year—a ratio of 8.8 improvements per year per employee. Goals and results are shown in Fig. 2.8.19, which also demonstrates that it took approximately 10 weeks from the day a problem was identified until the proposed improvement had been implemented. Furthermore, there was an average of approximately 250 problem items undergoing improvement at a given time, or about 8 to 10 per development team.

Customer/Supplier Relations

In productivity improvement through employee participation, the *customer* receives prime consideration. The customer's demands and satisfaction are the driving force for the development work.

In industrial operations, there are both *external customers* (those to whom the company is delivering its products and/or services) and *internal customers* (those engaged in the next process in a company's work with products and services). This means that all activities within a company have customers.

Previously it was mentioned that development teams were formed for organizational units and work areas within Elektrotryck so that the affected employees could focus on their own work area, being intimately familiar with its conditions, demands, equipment, machines, systems, and methods. In order to satisfy the external customers' demands and wishes, each development team cooperates with the internal customers' development teams through regular, collective team meetings.

The delivery teams prepare questions concerning their products and services with regard to quality, delivery, financial, personnel, and environmental issues. During the meeting, the customer team members present their demands and opinions, which are then jointly reformulated as problems directed to the delivery team and noted on a problems/suggestions/improvements form. This way, both teams will have an instrument for continued development work, which will be discussed and completed at subsequent meetings. A sketch in principle for customer and delivery consultation is shown in Fig. 2.8.20.

Through consultation between the customer and delivery teams, new points and problems relevant to other work areas and development teams arise, at which time a temporary

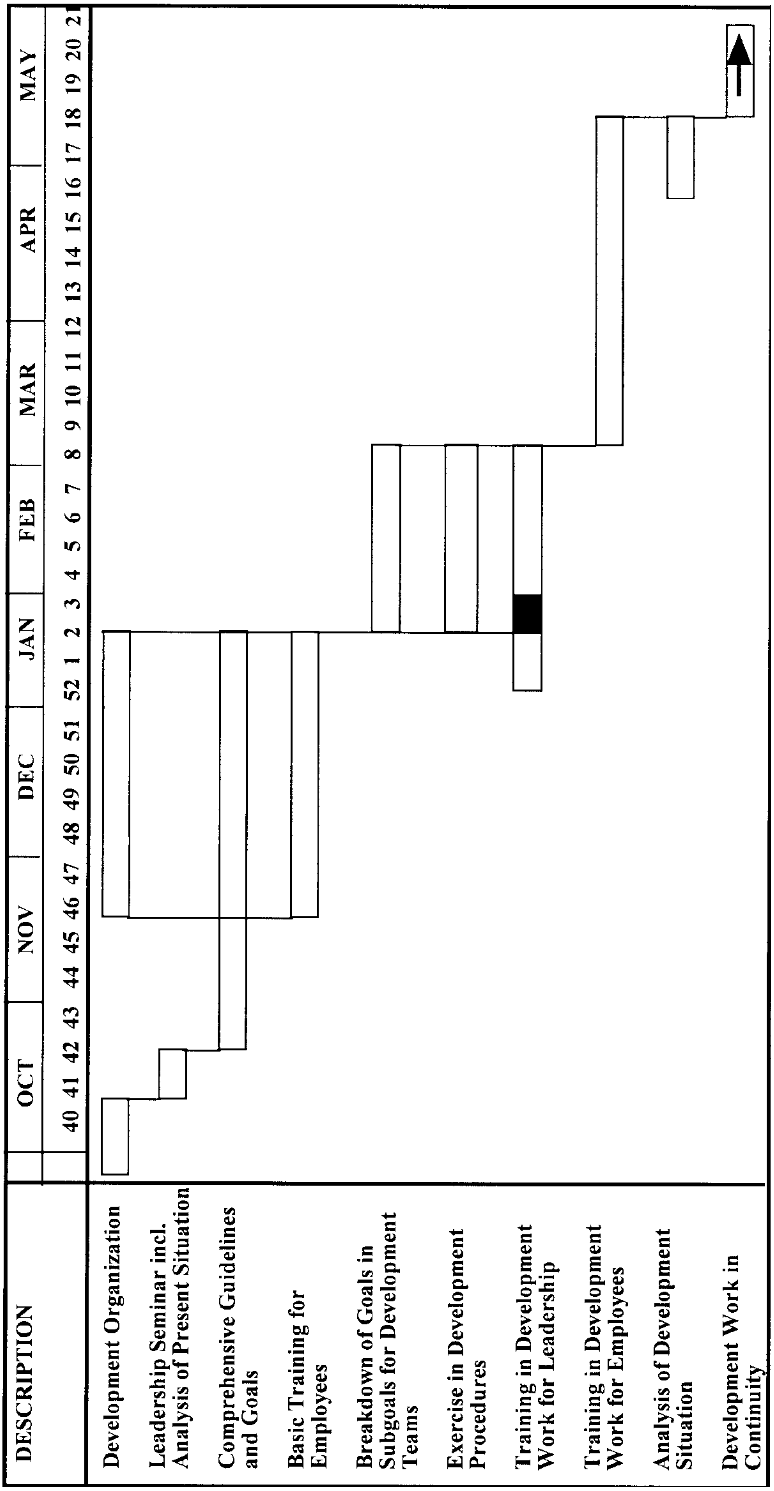
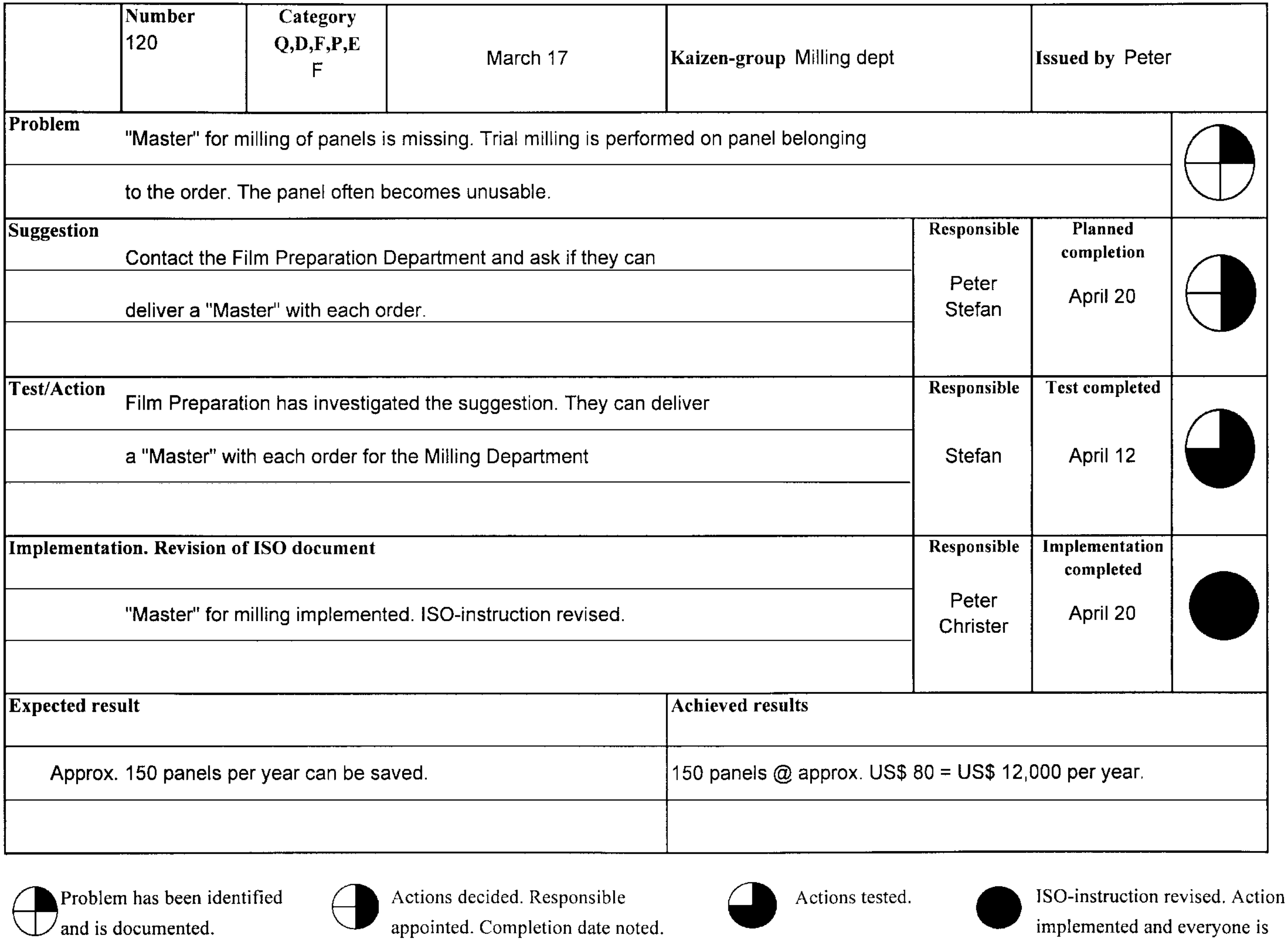


FIGURE 2.8.17 Master schedule for development.

SUGGESTION FOR IMPROVEMENT



Number 120	**Category** Q,D,F,P,E F	March 17	**Kaizen-group** Milling dept	**Issued by** Peter

Problem	"Master" for milling of panels is missing. Trial milling is performed on panel belonging to the order. The panel often becomes unusable.			◔
Suggestion	Contact the Film Preparation Department and ask if they can deliver a "Master" with each order.	**Responsible** Peter Stefan	**Planned completion** April 20	◑
Test/Action	Film Preparation has investigated the suggestion. They can deliver a "Master" with each order for the Milling Department	**Responsible** Stefan	**Test completed** April 12	◕
Implementation. Revision of ISO document	"Master" for milling implemented. ISO-instruction revised.	**Responsible** Peter Christer	**Implementation completed** April 20	●

Expected result	**Achieved results**
Approx. 150 panels per year can be saved.	150 panels @ approx. US$ 80 = US$ 12,000 per year.

◔ Problem has been identified and is documented.

◑ Actions decided. Responsible appointed. Completion date noted.

◕ Actions tested.

● ISO-instruction revised. Action implemented and everyone is

FIGURE 2.8.18 Example of problem solution.

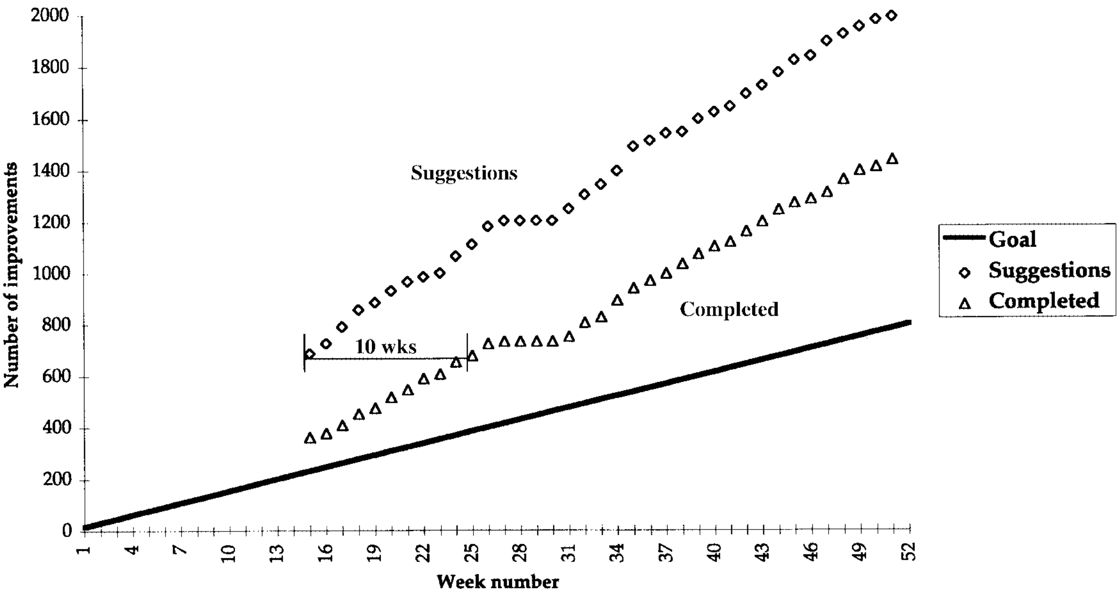


FIGURE 2.8.19 Improvement for the following year.

development team is formed, composed of members from concerned development team areas and specialists, as needed. Such a development team will be dissolved upon the completion of the project or assignment.

To approach the work from the perspective of customer/supplier relations is a very powerful way to tear down invisible walls and barriers that exist within various areas of the company. This strengthens cooperation and focuses development work for the benefit of the customers and, consequently, for the benefit of the company.

Improvements of the Workplace

Following the training period, approximately one month was allocated to exercises in development procedures and development methodology. Each development team started by improving its own workplace and work area. To achieve this, the development procedure known as "take care of your workplace, 5S" was applied, which constitutes a minirationalization program. This offered many opportunities to practice the remaining development procedures and methodology. The course of action for this process follows.

The principal goal was for everyone in the company to achieve, in short period of time, a more efficient and pleasant workplace. For comparison purposes, photographs of the workplaces were taken before the start and after the completion of the project. The results could therefore be demonstrated in both written and photographic form.

The 5S development consists of *s*ort, *s*ystematize, *s*ervice workplace, *s*upport comfortable environment, and *s*tandardize, working through each S in the order given. However, as each step overlapped another, an already completed S could be further applied as new ideas arose during the work process.

The work procedure was essentially the same for administration and production work. Here's how the development work for production was pursued.

CASE STUDY: PRODUCTIVITY IMPROVEMENT THROUGH EMPLOYEE PARTICIPATION

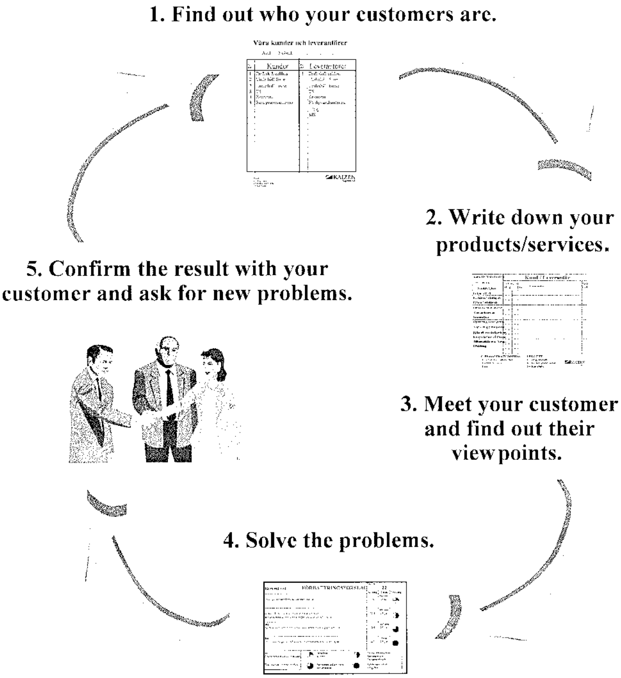

1. Find out who your customers are.
Våra kunder och leverantörer
Kunder
Leverantörer
KAIZEN
2. Write down your products/services.
3. Meet your customer and find out their viewpoints.
4. Solve the problems.
FÖRBÄTTRINGSFÖRSLAG
5. Confirm the result with your customer and ask for new problems.

FIGURE 2.8.20 Sketch in principle for customer/supplier consultation.

1. Sort
   - Study and decide what is necessary for efficient work from existing

     Machines, machine parts, fixtures, and tools

     Hand tools and tools common to the team

     Handling and storage equipment for materials

     Storage lockers

     Display areas and floor space
   - Mark unnecessary items with a red tag.

     This will remind team members that anything unnecessary must be removed from the workplace.

     On the red tags, note whether the unnecessary item will be moved into storage or scrapped. Unnecessary areas are also marked with a red tag.
   - Remove all unnecessary items from the workplace.

     Set up a temporary area near the workplace and move all unnecessary items there. This will free the workplace for subsequent development work.

     Rough-clean the workplace. After sorting, it is necessary to rough-clean the workplace, at least where relocations have occurred.

2. Systematize
    - Study, analyze, and test how the work will be done rationally.
    - Rearrange the workplace so that the work can be performed in the most efficient way.

      Position machines, machine parts, fixtures, and tools within convenient view and easy access.

      Place hand tools and handling equipment within convenient view and easy access.

      Set up material stands and material containers for efficient work.

      Place storage locker within easy access and arrange the contents for efficient work.
    - Place common tools and equipment, which are not used often, within convenient view and easy access in common setup areas.
3. Service workplace
    - Check and maintain machines, tools, and workplace equipment to avoid malfunction from wear and tear.
    - Defects and wear should be marked with a yellow tag as a reminder that corrective measures need to be taken and to confirm that the measure has been carried out.

      On the yellow tag, note larger defects and wear that need to be remedied by a specialist (repaired or replaced) as well as smaller defects and wear that can be rectified by the team itself.
    - Make certain to remedy defects and wear and tear.

      At the same time, check the condition of oils, lubrication, and so forth and remedy as needed.
4. Support comfortable environment
    - Clean machines, tools, and equipment.
    - Check and remedy defects such as humidity, drafts, bad lighting, painting, and so forth.
    - Clean and tidy up workplaces and surrounding areas.
    - Remove spill and waste.
5. Standardize
    - Establish simple, short descriptions of how to sort, systematize, and service the workplace.

Support a comfortable environment and standardize on a daily, weekly, and monthly basis to maintain a high standard at the workplace. Establish a checklist for how to continuously "take care of your workplace, 5S."

An example of the implementation of 5S is shown in Fig. 2.8.21.

Elektrotryck allocated one hour per day for five weeks in order to implement 5S at the workplaces. All employees in a development team implemented 5S simultaneously. The time requirement for maintaining 5S standards is approximately five minutes per day per employee, provided he or she is thinking of 5S as part of the daily work routine.

During this development work, many ideas emerged that could not be remedied immediately, partly because of the scope and partly because of the effect on other workplaces. These problems and suggestions were noted on problems/suggestions/improvements forms as they appeared and were passed on to the development team. This led to a substantial increase in assignments.

Through the application of 5S, everyone at Elektrotryck was given the opportunity to substantially improve their own work situation. As a result, productivity improvement of anywhere from 10 to 15 percent was achieved, and the workplaces became more pleasant.

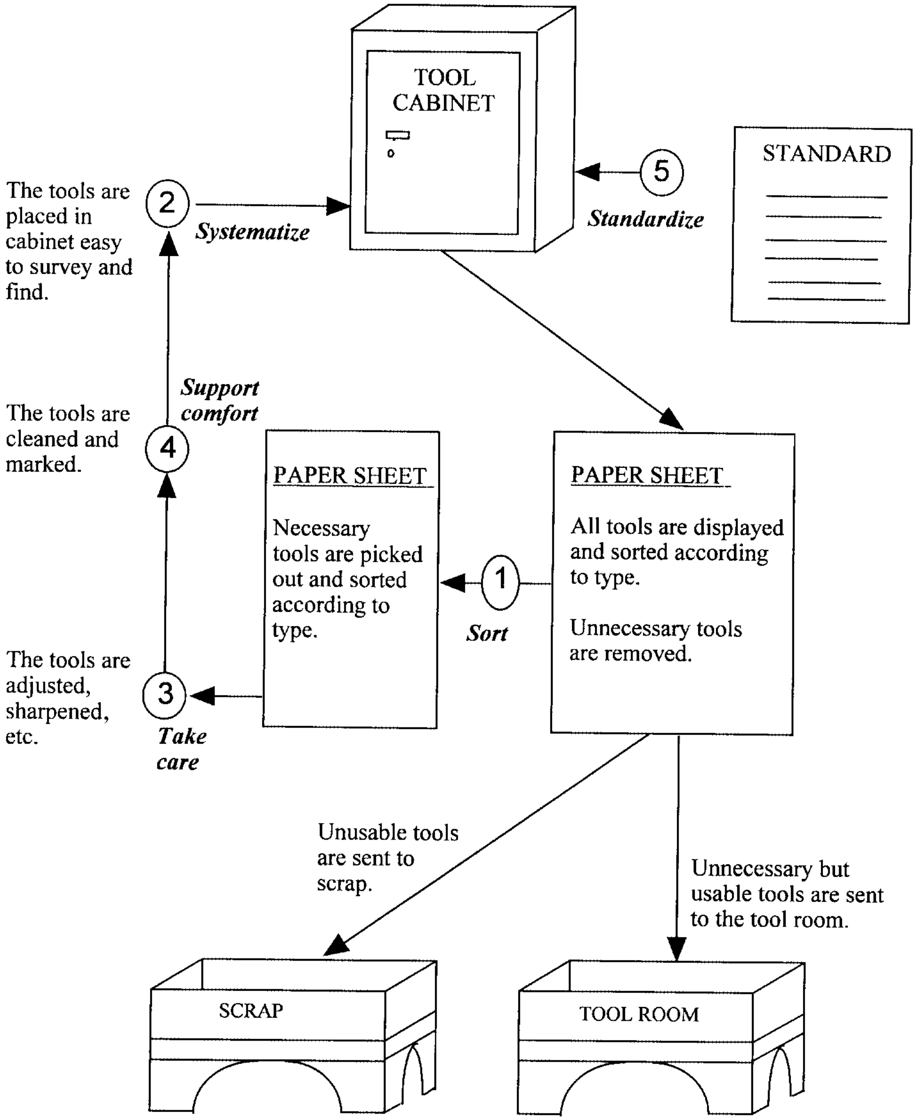

TOOL CABINET
STANDARD
5
Standardize
The tools are placed in cabinet easy to survey and find.
2
Systematize
Support comfort
The tools are cleaned and marked.
4
PAPER SHEET
Necessary tools are picked out and sorted according to type.
PAPER SHEET
All tools are displayed and sorted according to type.
Unnecessary tools are removed.
1
Sort
The tools are adjusted, sharpened, etc.
3
Take care
Unusable tools are sent to scrap.
Unnecessary but usable tools are sent to the tool room.
SCRAP
TOOL ROOM

FIGURE 2.8.21 5S for a tool cabinet.

TRAINING IN DEVELOPMENT WORK

After training and exercises in procedures and methods, the improvement work will be implemented and become a natural part of the daily routine. In order to make a quick start and to achieve tangible improvements, a one-week-long training seminar was completed by all development teams at Elektrotryck. This included about one hour to prepare the work each day. The remainder of the day consisted of practical development work in the respective teams. During the seminar, the following topics were covered:

- Analysis of waste and unnecessary items
- Improvement work
- Skill development for flexibility
- Reporting on results

The management teams completed their training seminars at Ekerö and Timrå during the development teams' practice sessions so that they would then be able to conduct the seminars for their respective development teams.

As the development teams completed their basic training and began their exercises in development procedures, they prepared for a one-week seminar in practical training by compiling technical data and descriptions and arranging a room, material, and equipment for meetings.

After completing the seminar, the development teams were ready, with the support of the management and coordinator, to continuously work with productivity development on a daily basis.

The completion of training seminars in development work is described next.

Analysis of Waste and Unnecessary Items (MUDA)

The customer is prepared to pay for only material, processes, and labor that add value to the product or service. In product- or service-producing businesses, the value-adding activities do not amount to more than 10 to 30 percent of the costs. The rest is waste or unnecessary, adding no value for the customer, and therefore ought to be reduced to a minimum. (See Fig. 2.8.22.)

At Elektrotryck, the development teams began improvements in the following ways:

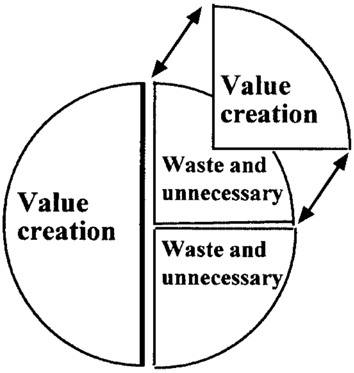


FIGURE 2.8.22 Value creation/waste and unnecessary items.

- Identifying waste and unnecessary items
- Reducing or eliminating waste and unnecessary items
- Providing value creation

Waste and unnecessary items are transformed during the development work into problems, after which the development team processes the problems using the P-D-C-A procedure. Through this procedure, the development teams were furnished with many problems, and consequently a large number of improvement tasks, even during the training stage, when all employees are trained to think in terms of creating value versus not creating value. In this way, a continuous flow of new problems and improvement suggestions were brought to the development team.

Waste and unnecessary items occur in both production and administrative work within the following areas:

- Excess production
- Work processes
- Rejections and rework
- Motions and movements
- Transportation
- Inventory, storage, stock
- Waiting

Excess Production. To produce more products than is necessary in a production facility causes heavy losses due to material, labor, machines, and storage facilities being used prematurely, as well as increased costs for administration and transportation. Excess production can have the following causes:

—Ignoring needs from the next process
—Allowing machines to produce more than necessary due to overcapacity
—Desiring to increase the efficiency of one's own process
—Desiring to give the operator elbowroom

Work Processes. Waste and unnecessary items in the processes are caused by inefficient procedures or methods and can often be attacked by work simplification. For example, waste and unnecessary process work may occur when the operator uses his or her left hand for holding instead of productive work or when the inspection task has been separated from its work process.

Rejections and Rework. Attempting to do it right the first time is the best method of avoiding rejections and rework. Another method is to use one-piece flow production. This applies to both production and administration work.

Motions and Movements. All motions and movements are waste, and unnecessary motions must be avoided. Therefore, all work procedures that involve motions or movements should be avoided, especially those that demand bends and stretches, which are physically strenuous. Waste and unnecessary motions occur, for example, when an operator is moving objects (walking with objects, picking up objects, taking down objects).

Transportation. Waste and unnecessary motions occur during transportation to and from processes and to, within, and from warehouses, storage facilities, and stockrooms.

Inventory, Storage, Stock. Inventory, storage, and stock constitute waste and unnecessary items. The costs involved include costs for administrative work.

Waiting. Some waste and unnecessary items occur when an operator is forced to wait due to lack of work or when an operator is overseeing facilities or machines.

The training seminars began with an analysis of waste and unnecessary items. The development team was divided into analysis teams consisting of two to three participants. An analysis team studied its part of the team's work area for one to two hours. After they discussed and described types of waste and unnecessary items, the analysis teams gathered and reported to each other on their findings, which were then compiled for the entire work area. Based on results of the analysis, the development team made a rough assessment of the occurrence of waste and unnecessary items. Examples of analysis and assessment of waste and unnecessary items from different development teams are shown in Figs. 2.8.23 and 2.8.24.

This study allowed the development teams to gain a good overview of the occurrence of waste and unnecessary items, categorized by type. Every noted occurrence of waste and unnecessary items was transformed into a problem, which was then recorded on a problems/suggestions/improvements form. The analysis of waste and unnecessary items made up the first important step of the development team's problem-solving activities.

Improvement Work

Through the analysis of waste and unnecessary items, the development team noted a large number of problems on problems/suggestions/improvements forms. To efficiently organize the improvement work, each new problem was added on a summary sheet exhibiting the team's in-progress improvements. The problem was then given a running number, and notations were made regarding the problem area (quality, delivery, finance, personnel) and person responsible for the development work as well as development status (P-D-C-A).

All problems/suggestions/improvements forms as well as summary sheets were kept in a development catalog organized according to development status. At each team meeting, all the problems/suggestions/improvements forms in the catalog were reviewed. Those responsible reported on progress being made. Decisions were made regarding future developments, and a notation of the new status was made in the catalog. Completed work was marked with a black bullet (●). The development catalog was kept in the development team's meeting room. A summary of the development team's ongoing improvements and an example of a development catalog can be seen in Figs. 2.8.25 and 2.8.26.

The development team found numerous problems in connection with the analysis of waste and unnecessary items. The problems were formulated in conjunction with the transition of the company's comprehensive goals to goals for the individual team. This way, the improvement work covered a wide range of development areas, most of which were interconnected and affected by each other. An overview of the development areas and how they can connect is shown in Fig. 2.8.27.

By first asking what creates value in the work area, the development teams sought the ideal way to carry out their assignments. Then the development work began, and measures were taken to reduce the difference between the ideal design of the work and the current design.

Over time, the team members became conscious of their ability to change their work design for the better via process planning, process combinations, process control, and technology. The development work, both in production and administration, was directed toward so-called flow production, where it had not been previously applied. In *flow production,* products and services are produced without interruption throughout the entire production

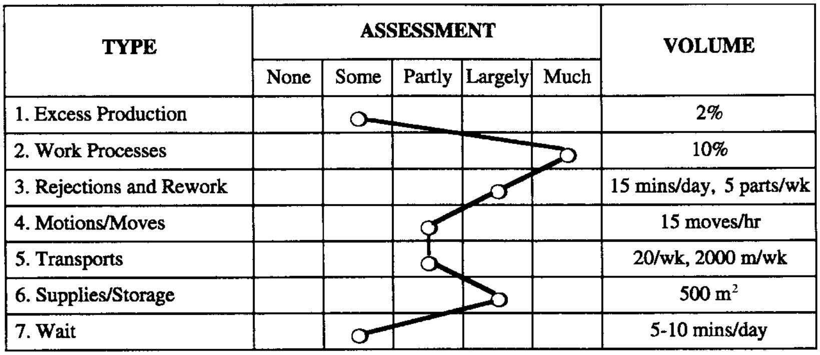
Type	DESCRIPTION OF AREAS, WEIGHT, ETC.
1 EXCESS PRODUCTION	- We manufacture more than needed for the moment. - Uneven workload between departments and individuals, - Too many non-selling visits.
2 WORK PROCESS	- Cannot find my tool. Searching for documents among binders and computers. - Alignment of slewing bracket is very difficult and takes time. - It takes 3 weeks from product is sold until manufacturing can start.
3 REJECTION AND REWORK	- 15% of the material goes to waste. - The design was not good because of inadequate preparation study. - Our claims have lead to increased discounts in order to be able to sell our products.
4 MOTIONS/ MOVES	- Very heavy lifts (15 kg, 100 times/day). - The feed rate on the machine is low. - Sitting at the terminal all day causes problem in the shoulders.
5 TRANSPORTS	- Truck transports. - Long and expensive transports because of long distances. - Extensive travelling.
6 SUPPLIES/ STORAGE	- Material ready for 4 days' production. - The same thing is located in 5 places (we do not know what is available). - The stock turnover rate is 10 times/year.
7 WAIT	- Wait for the maintenance personnel to come. - Wait for everyone to be in time for meeting (10 minutes). - Wait for decisions.

FIGURE 2.8.23 Analysis of types of waste and unnecessary items.

and administration process, as opposed to *batch production,* in which products and services are produced in lots, operation by operation.

This reduced waste and unnecessary items (especially excess production, rejections and rework, transportation, and inventory/storage/stock) and simplified the processes. An overview of flow production versus batch production shows that flow production is simpler and less costly. Figure 2.8.28 explains why flow production was favored in work design.

CASE STUDY: PRODUCTIVITY IMPROVEMENT THROUGH EMPLOYEE PARTICIPATION



TYPE	ASSESSMENT					VOLUME
	None	Some	Partly	Largely	Much	
1. Excess Production		○				2%
2. Work Processes					○	10%
3. Rejections and Rework				○		15 mins/day, 5 parts/wk
4. Motions/Moves			○			15 moves/hr
5. Transports			○			20/wk, 2000 m/wk
6. Supplies/Storage				○		500 m^2
7. Wait		○				5-10 mins/day

The volume can be expressed in:

* Length * Surface * Volume * Weight * Quantity * Time * Money, etc.

FIGURE 2.8.24 Assessment of the occurrence of waste and unnecessary items.

	PROBLEMS/SUGGESTIONS/IMPROVEMENTS SUMMARY			
Group:	**Soldering Machine, Timrå**			
No.	**Description**	**Q, D, F, P**	**Resp**	**Status**
1	**Master for panels**	F	PJ,SL	●
2	**Straightening of input material**	Q	RG	◕
3	**Clamping of panels in fixture**	Q	PF	◑
4	**Adjustment of cooling**	Q	KA	◑
5	**Handling of finished panels**	Q,D	HS	◔
6	**Meeting place for the group**	P	GN	●
				⊕

Problem area: Q = Quality, D = Delivery, F = Finance, P = Personnel

FIGURE 2.8.25 Summary of problems/suggestions/improvements.

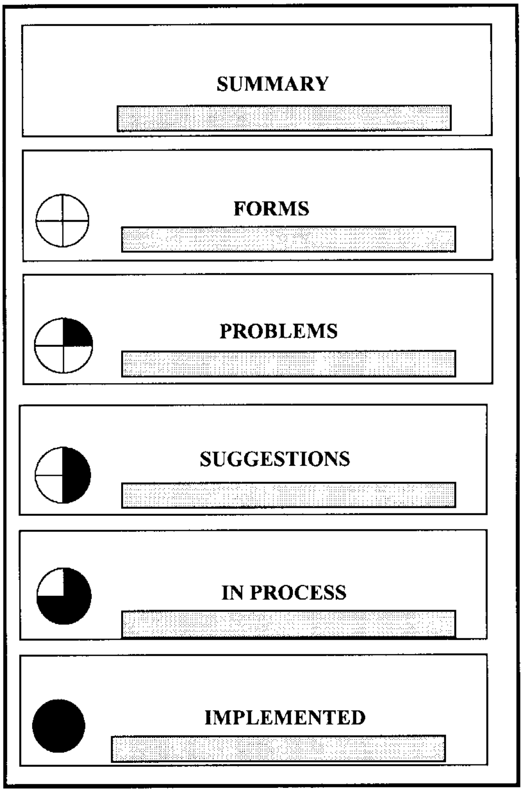


FIGURE 2.8.26 Development catalog.

Skill Development for Flexibility

As a result of the improvements made by the development teams, the team members' assignments will change. This often demands versatility and flexibility. As an example, the transition from batch production to flow production requires knowledge of all operations and work elements within the flow team. Furthermore, additional demands are placed on a majority of the employees' knowledge concerning changeovers, inspection of the team's own work, machine and equipment maintenance, and planning, handling, and control of the team's production.

Skill development for the members of the development team, in order to meet the demands on versatility and flexibility, was planned and started by each team during the one-week seminar. This was accomplished as follows:

- Defining knowledge requirements
- Planning education/training according to need
- Training based on established plans

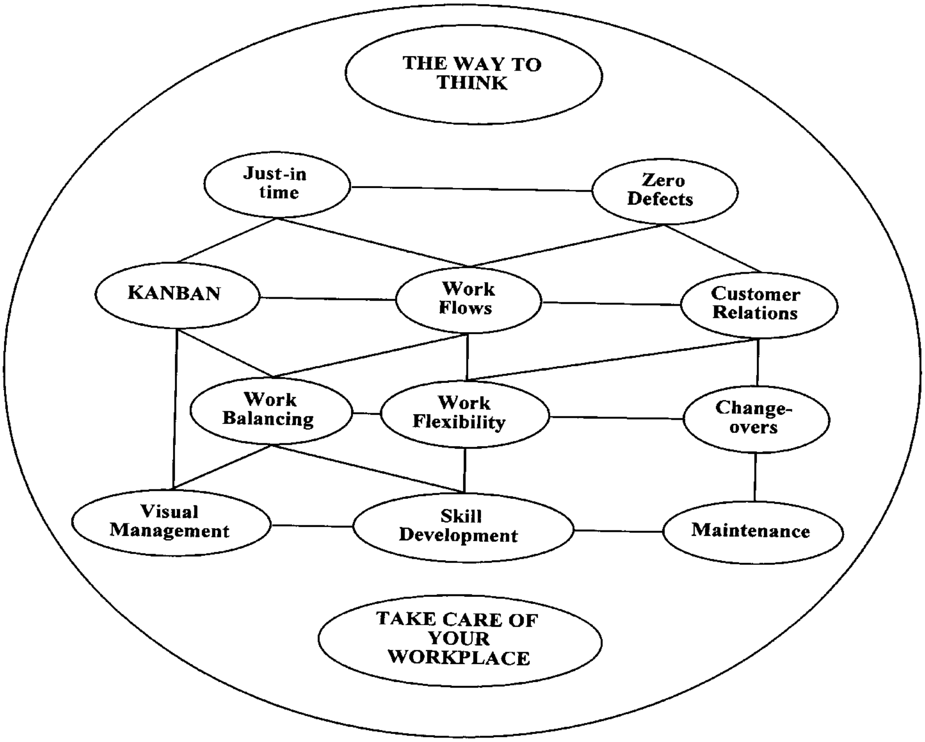

THE WAY TO THINK
Just-in time
Zero Defects
KANBAN
Work Flows
Customer Relations
Work Balancing
Work Flexibility
Change-overs
Visual Management
Skill Development
Maintenance
TAKE CARE OF YOUR WORKPLACE

FIGURE 2.8.27 Development areas and their relationships.

Each manager and employee was further educated and trained, according to need and plan, for professional advancement, for other jobs, and for assignments requiring higher qualifications. The need for skill development was continuously analyzed within the development teams and was reported on a so-called skills matrix. This matrix was placed in the team's meeting room, where notations on progress were continuously made. An example of a skill development matrix for a development team is shown in Fig. 2.8.29.

The education/training was completed to a large extent with the assistance of employees possessing the necessary skills and ability to instruct. Through the systematic application of skill development according to need the development teams became

- More flexible during variations in workload and other temporary changes
- Capable of performing their tasks even during the absence of team members
- In large part independent of maintenance capacity
- Eager to take on responsibilities for planning, direction, and results

The way of thinking and the way of working, including skill development according to need, resulted in managers and employees becoming more interested in and satisfied with their work.

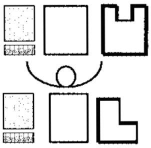
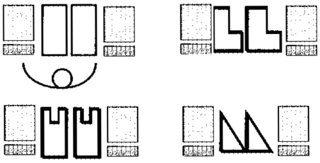
PRODUCTION FACTORS	FLOW 	BATCH 
MACHINERY	GENERAL	SPECIALIZED
SPACE	SMALL	LARGE
PERSONNEL QUALIFICATIONS	BROAD	SPECIALIZED
BATCH SIZE	SMALL	LARGE
CHANGEOVERS	SIMPLE	COMPLEX
QUALITY	ZERO DEFECTS	BATCH BY BATCH
THROUGHPUT TIMES	SHORT	LONG
TRANSPORT NEEDS	MINOR	CONSIDERABLE
WORK IN PROCESS	LIMITED	SUBSTANTIAL

FIGURE 2.8.28 Overview of development opportunities.

Report of Results

During the final day of the one-week seminar the results were compiled. The development teams summarized the results of both the implemented improvements and those expected from improvements in progress. The results were divided into the problem areas of quality, delivery, finance, and personnel (personnel includes environment). An example of results from a development team during the one-week seminar is shown in Fig. 2.8.30.

Each development team reported its development results at the end of the seminar. During the seminar week, the development teams established procedures and means to continuously report the team's goals, improvement work, and achieved results in a simple and clear way. The development team's goals were kept in a binder at the meeting place. This could contain goals concerning the following:

- Claims
- Rejections
- Rework
- Delivery reliability
- Throughput time
- Material costs
- Productivity (volume, delays, etc.)
- Expenses
- Improvements

CASE STUDY: PRODUCTIVITY IMPROVEMENT THROUGH EMPLOYEE PARTICIPATION

NAME	PROCESS									
	Deburring	Chem. Copper	Chem/El. Gold	El. plating	Etching	Tinning	Test/ Analysis	Maintenance	First Aid	KAIZEN
AHMAD	● ⊕	◑ ⊕	● ⊕	⊕ ⊕	◕ ⊕	● ⊕	● ⊕	● ◔	⊕ ⊕	● ⊕
AINO	◕ ⊕	⊕ ⊕	● ⊕	● ⊕	⊕ ⊕	● ◕	⊕ ⊕	◔ ⊕	● ⊕	● ◑
DANIEL	⊕ ⊕	● ⊕	⊕ ⊕	◑ ⊕	● ⊕	⊕ ⊕	◕ ⊕	◕ ⊕	◑ ⊕	◑ ⊕
DAVID	◑ ⊕	◔ ⊕	◕ ⊕	● ⊕	⊕ ⊕	● ⊕	⊕ ⊕	● ⊕	⊕ ⊕	◕ ⊕
MIKAEL	● ●	● ●	◑ ⊕	● ●	● ●	⊕ ⊕	● ●	◕ ⊕	⊕ ⊕	● ⊕
PATRIK	● ⊕	⊕ ⊕	● ◕	◑ ⊕	◑ ⊕	◕ ⊕	◑ ⊕	● ●	⊕ ⊕	● ⊕
ROINE	● ●	● ●	⊕ ⊕	● ●	● ●	◔ ⊕	● ●	◑ ⊕	◕ ⊕	● ⊕

Legend:
◔ = Planned
◑ = Affirmed Start
◕ = In Process
● = Completed
⊕ (left) = Operator
⊕ (right) = Instructor

FIGURE 2.8.29 Skill development matrix for a development team.

- Skill development
- Safety

The goals were formulated in such a manner that they could be continuously compared to achieved results. Figure 2.8.31 shows the goals and follow-up of results for the marketing team's claims.

The team's development catalog, which constituted the main tool for the team's daily improvement work, was kept in the meeting room. Furthermore, each development team acquired a magnetic whiteboard, 2 × 1 m (6 × 3 ft), for visual and continuous reporting of improvement work in process. The board was divided into five fields. In the field designated for improvements, before-and-after pictures of the current situation were shown, along with a graph of the number of suggestions and improvements the team had achieved compared with established goals. The other four fields displayed current situations from the team's improvement work regarding quality, delivery, finance, and personnel. (See Fig. 2.8.32.)

The next section describes the development teams' system of reporting goals, improvements, and achieved results.

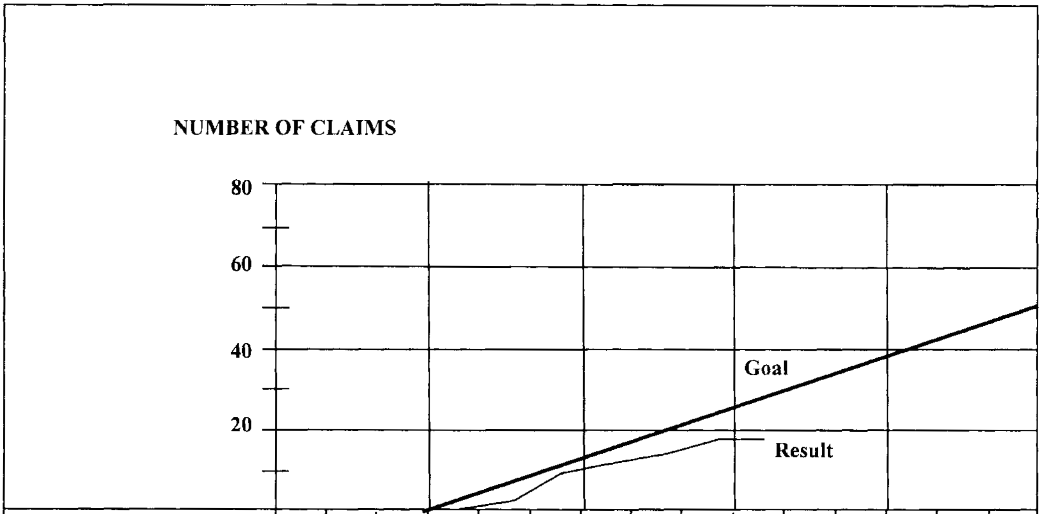
CONTINUOUS DEVELOPMENT WORK

Productivity improvement through employee participation was introduced and started so that everyone within Elektrotryck would be working with improvements in organized

AREA	Problems	In Process	Imple-mented	EXAMPLES OF RESULTS FROM IMPLEMENTED IMPROVEMENTS	
QUALITY	16	9	7	- BETTER INSTRUCTIONS	170 hrs / year
DELIVERY	6	2	4	- STORAGE REPLACEMENT	80 m^2 less area, 13%
FINANCE	18	11	7	- MATERIAL SAVINGS	US$ 12,000 /year
PERSONNEL	17	7	10	- WORKPLACE IMPROVEMENTS	10,000 kneebends/week
TOTAL	57	29	28	- DEFECTS AND REWORK	Material 3%, work 400 hrs / year
				- STORAGE VOLUME	Area demand 80 m^2 less
				- WORK SIMPLIFICATION, MATERIAL SAVINGS	Work 200 hrs / year, Material US$ 16,000 / year
				- WORKPLACE IMPROVEMENTS	Simplification, Ergonomy, Comfort

FIGURE 2.8.30 Example from a development team during the one-week seminar.

CASE STUDY: PRODUCTIVITY IMPROVEMENT THROUGH EMPLOYEE PARTICIPATION



MONTH					1	2	3	4	5	6	7	8	9	10	11	12
GOAL	Per month				5	5	5	5	5	4	4	4	4	4	4	4
	Accumulated				5	10	15	20	25	29	33	37	41	45	49	53
RESULT	Per month				1	6	3	4	3	0	0					
	Accumulated				1	7	10	14	17	19	19					

FIGURE 2.8.31 Goals and follow-up of results for the marketing group's claims.

teams according to established goals by the following midyear. During the fall, the development work continued with great enthusiasm, at which time supplementary training in procedures and methods was completed, as well as training in practical development work. At the same time, a second analysis of the technical development status was made. Based on this analysis, goals, organization, and work procedures were established for the company's consistent development.

Analysis of the Development Situation

The steering committee analyzed the technical development status during the fall of the year following the initial phase. This analysis included the technical development status during the initial phase. The summary of Elektrotryck's development situation after the initial phase is shown in Fig. 2.8.33. As the analysis shows, all the areas under development were considered to be of great importance and significance (value 3.0).

The following development areas were considered in need of being supplemented before the development was implemented and applied to the fullest extent:

- Guidelines and goals
- Taking care of your workplace
- Practical development work

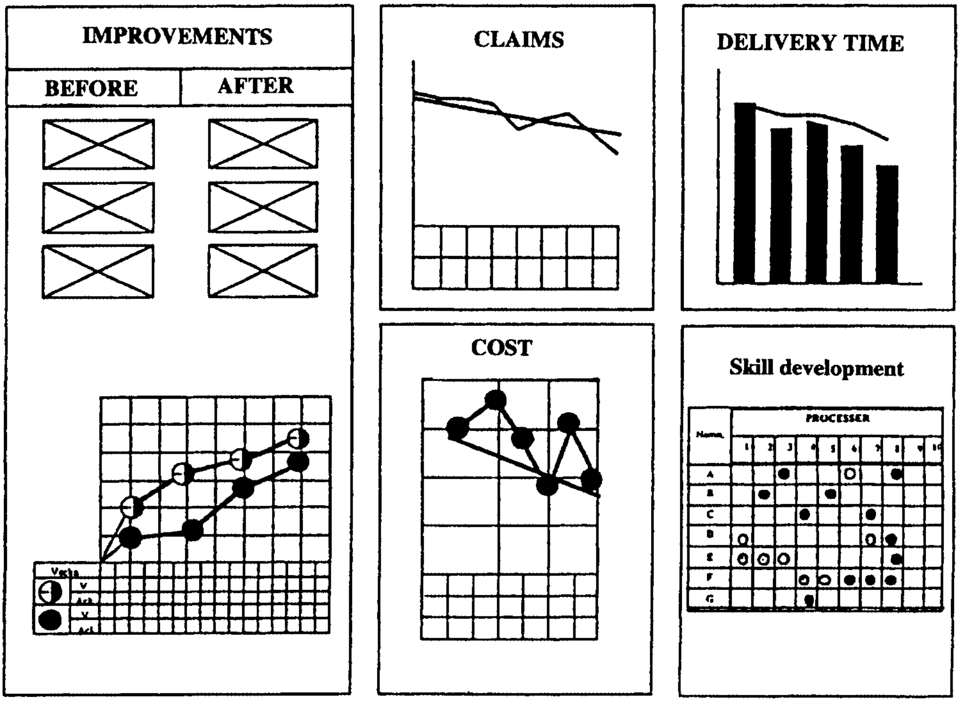


FIGURE 2.8.32 Improvement work in process.

The development phase resulted in a total improvement from a value of 1.7 to 2.8.

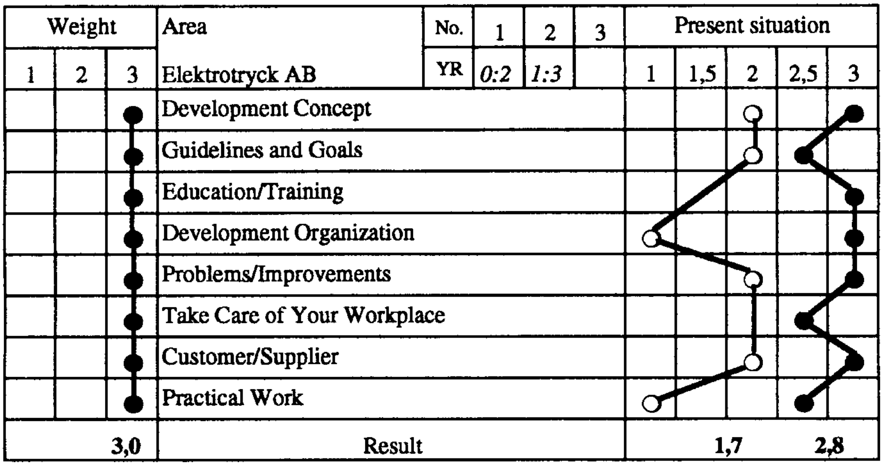
Elektrotryck's management, a team consisting of the managing director, administrative director, technical director, plant manager for the Timrå plant, and the program coordinator, holds regular meetings with each development team. From these meetings, the following viewpoints have emerged as candidates for the continuous development work:

- The leaders of the development teams must receive additional training, especially in goal breakdown, development methods, and working within a project environment.
- All employees must have a plan for cross training in several jobs to increase flexibility.
- New employees will be trained in current jobs, organization, and work procedures, as well as in development procedures.

Further Development Based on the Development Situation

Parallel to the continuous development work, further developments occurred:

- Approximately 10 development team leaders received additional training of 80 hours, so-called facilitator training. This training included (in addition to development concepts, procedures, and methods) production economy, just-in-time, and development in a project environment. This enhanced the knowledge base for further development, for support of the development teams' work, and for the training of new employees.



Weight		Present situation	
3	Very important. Great significance.	3	Development completed. Application to full extent.
2	Less important. Some significance.	2	Development in progress. Application to a certain extent.
1	Not important. No significance.	1	Development not started. No application.

○ Initial situation.
● After initial phase.

FIGURE 2.8.33 Technical development status after the initial phase.

- Recruiting is planned to take place at seven occasions per year with two to three people per occasion. Education/training will be completed according to prepared plans during a 20-week period, during which evaluations and selections will be made. In addition to training in job skills, development work in the areas of quality, delivery, finance, and maintenance will also be covered. One full-time employee is appointed for this task.
- Development teams occasionally encounter problems that are so complex that they extend over several development teams' areas of responsibility. Special teams, called *project teams,* are then formed by the affected development teams. Under the steering committee's leadership, these project teams solve the problem at hand. As a guide for dealing with problems of a project character, the *quality gap audit* (QGA) can be applied.

RESULTS

Comprehensive Results

From the beginning of the first year in which the improvement program was initiated to the following year, annual revenue at Elektrotryck AB showed an increase of 14 percent. The total product manufacturing costs decreased by 15 percent during this period. One factor contributing to the company's improved results was productivity improvement through employee participation. The development teams handled more than 2000 improvement suggestions within the areas of quality, delivery, productivity, finance, personnel, and environment during the introductory and start-up phases, during which time most of the improvement suggestions also were implemented.

Statements by Managers and Employees

The annual report the year following the development work included these words:

> The significant investment made in productivity improvement through employee participation (Kaizen) that began at the end of the initial year, got its major breakthrough in the spring of the following year. It became evident that Kaizen is not simply Eastern magic, turning our employees into robots. Instead it is a variant of honest Swedish common sense, giving our employees the possibility to influence their own work, which increases involvement and awareness.
>
> We believed from the outset that Kaizen would enable us to achieve better quality and lower costs. With the answer key in hand after our first Kaizen year, we can say that without Kaizen we would not have achieved such admirable results this year.
>
> We have learned a new way of thinking and would like to thank everyone who has made the Kaizen work such a success.

Employees from *ET-Bladet* (Elektrotryck's newsletter) offered the following:

> Kaizen is the common sense which we have not taken time to apply earlier because production has always come first. Customer/Supplier meetings are experienced as very positive. Our supplier came to us and asked us what problems we had, as opposed to us going and complaining, as it used to be. The positive spirit that arose made us feel that we were pulling in the same direction.
>
> The Kem team at Timrå had an extensive discussion about the stock of raw materials and how the loading might be managed more expeditiously. An extensive refurbishment of the stockroom resulted in the elimination of many unnecessary steps and backbends. Furthermore, the work is now done much faster.
>
> Many valuable suggestions were really brought forth. Ideas that had been smoldering earlier were now given new life and could be developed. We removed a wall that separated electrical testing from inspection and achieved better flow and community. Through rearrangements we changed the way in which the work was done and could, among other things, eliminate 10,000 knee bends per week. We also did away with duplication work by computerizing the log book. Besides, we removed a "corridor" full of concrete "Muda." We are motivated to work with Kaizen through daily meetings. We see the results.

And here are closing words from Anders Björsell, managing director of Elektrotryck AB:

> This case study has described the implementation of KAIZEN in the entire Elektrotryck organization. It became evident that the Japanese mysticism was mostly about applied common sense. I believe the most important aspect of the Japanese to be the new words we have learned, KAIZEN, GEMBA and MUDA. Because every person has their own assessment of words in their own language, misunderstandings can often arise despite the fact that they are speaking to each other in their mother tongue. To implement new words that everyone learns simultaneously is genial! The words have no burdensome valuation except our own common history.
>
> After a very exciting and educational time during the start-up of our KAIZEN-work, when we in fact succeeded in bringing in a new culture, we are now progressing into keeping the KAIZEN work alive. If the leadership now believes that KAIZEN sustains itself, we would be in trouble. The most important thing to keep the KAIZEN-work alive is the commitment by the leadership. Never forget that!

ACKNOWLEDGMENTS

My sincere thanks to **Eva Landqvist** at Elektrotryck for her capable and inspired work with the text and illustrations and to **Christin Zandin** for her commendable translation of the original Swedish text into American English.

BIOGRAPHY

Lennart Gustavsson has been a recognized industrial engineer, productivity developer, and management consultant in industry worldwide for more than 50 years. He has an engineering degree from ETF in Västerås, Sweden, and has received business management education in Sweden and at Columbia University in New York.

Gustavsson commenced his career with ASEA (ABB), first as an industrial engineer and subsequently as manager of the industrial engineering department in the Ludvika, Sweden, facility. After five years as industrial engineering manager at KMW (cellulose and paper manufacturing machines) and five years at Götaverken (commercial ships), Gustavsson was employed by H. B. Maynard and Company, Inc, where he was CEO for Maynard Shipbuilding Consultants for 10 years, followed by successive positions as CEO and COO for Maynard Sweden and Maynard Europe over the next 15 years. Thereafter, Kaizen Institute, Europe, employed Gustavsson, who later became chairman and COO for Kaizen Support AB in Sweden. Throughout his consulting career, Gustavsson has worked in a large number of industries and organizations in Europe, America, and Asia.

CHAPTER 2.9

CASE STUDY: REDUCING LABOR COSTS USING INDUSTRIAL ENGINEERING TECHNIQUES

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To achieve productivity improvements in manufacturing companies, application of new technology or adoption of mass production may not always be possible. The most practical approach is to attack the work process itself—that is, review and redesign the operations and apply automation and mechanization. In such cases, a productivity audit employing industrial engineering (IE) techniques is used for evaluating the existing manufacturing situation and identifying the potential for increased productivity. Additional industrial engineering methods are applied to develop improvement opportunities.

In this chapter, we introduce various industrial engineering techniques and use a case study to show how these techniques are applied in practice. The case study presented is from Company A, a bathtub manufacturer. The improvement process began with an audit of the current productivity situation. Then, following a master plan, productivity improvement actions were taken one by one. The result was a 20 percent reduction in cost after a two-year project. Because it is not possible to cover all aspects of the project in this chapter, the focus will be on the activities aimed at the reduction of labor cost. We also explain how the scope of the application of industrial engineering techniques is expanding.

INTRODUCTION

Productivity improvement measures can be roughly classified into four groups: (1) redesign of operations, (2) automation and mechanization, (3) use of mass production, and (4) application of new technology—each of which can be effective in specific situations. However, in practice, the opportunities to apply appropriate new technology may be few. In addition, with increased diversification of customer demands resulting in more product models, fewer products can be made in volumes large enough to justify mass production. Consequently, when it comes to productivity improvements in manufacturing companies, the approach that is usually the most effective is to focus on the work process itself. Improvements are then made through redesign of the operations and application of automation and/or mechanization.

The techniques for accurately evaluating the actual situation of a manufacturing process, identifying the potential for increased productivity, and identifying the approaches for making improvements fall within the scope of industrial engineering. Through continuous development and refinement, IE technology for many years has been applied to solve a variety of problems, and the technology is still effective. However, in today's world, not only because manufacturing processes have become more complicated but also due to more varied product mixes and greater diversification of customer requirements, the actual IE techniques must be adapted to each situation as they are applied.

Industrial engineering techniques can be used for two main purposes: (1) to discover problem areas in the manufacturing process being studied, and (2) to solve those problems in a practical and concrete way. In this chapter, the use of IE techniques in the audit stage of a productivity improvement project will be introduced as well as an actual case study of the application of IE techniques to achieve productivity improvements. Other chapters of this handbook describe specific IE techniques.

BACKGROUND OF THE CASE STUDY

The situation at Company A, a bathtub manufacturer, prior to starting the productivity improvement effort was as follows.

First, the bathtub business had experienced major progress in the area of product materials. Recently, customers had begun to demand much more advanced products than before—for example, products made of artificial marble. In pace with this trend toward more sophisticated products, the market was strong and Company A was forecasting a 30 to 50 percent growth in production volume over the following three years. On the other hand, price competition was becoming severe, and for the two years prior to launching the improvement activities, the bathtub business of Company A had been in the red.

The cost structure of the product was 60 percent materials, 20 percent processing cost (cost of in-house labor and subcontracted processing), and 20 percent other costs. There was a strong possibility of further increases in both material and processing costs. Moreover, accompanying the trend toward more sophisticated products, at the factory level, was a substantial variation both in the first-pass yield (number of nondefective products not needing rework ÷ the number of units processed) and the final yield. In addition, while the forecast for larger future production volumes (in response to greater demand) was welcomed, there was a concern over increasing labor cost. Other potential problems included finding and keeping a sufficient number of qualified employees. If the traditional staffing standards were kept, many additional employees would be needed, and a drop in the average skill level was likely to occur.

With this situation as a background, Company A organized a project team that included outside consultants. The mission of the team was to initiate activities aimed at productivity improvement and increased profitability.

Productivity improvement projects, in this case, are generally conducted in three phases as shown in Fig. 2.9.1. Phase I, productivity audit, and phase II, short-term problem solving, will be discussed in the subsequent sections. A general introduction to the methods used and a case study of labor cost reduction through the application of IE techniques will also be covered.

PRODUCTIVITY AUDIT AND DEVELOPMENT OF A PRODUCTIVITY IMPROVEMENT MASTER PLAN (PHASE I)

The main factors contributing to the success of any productivity improvement project are (1) to correctly understand the present situation in regard to productivity, (2) to clearly identify the problems, and (3) to apply appropriate IE techniques to achieve and maintain improve-

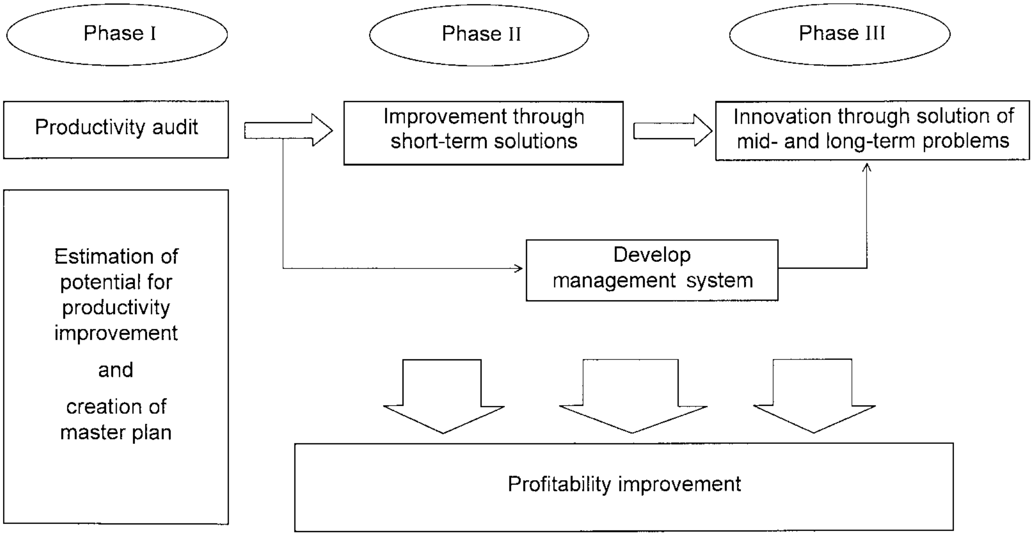

Phase I
Phase II
Phase III
Productivity audit
Improvement through short-term solutions
Innovation through solution of mid- and long-term problems
Estimation of potential for productivity improvement
and
creation of master plan
Develop management system
Profitability improvement

FIGURE 2.9.1 Flow of productivity improvement activity.

ments. Of course, to tie the productivity improvement results to an actual improvement in business performance, during the audit phase it is necessary to clarify the fundamental objectives of the improvement in productivity.

Industrial engineering techniques are useful for making improvements in individual situations, but they are also valuable in the audit phase for correctly evaluating the existing situation and for quantifying the potential for improvement. To evaluate the existing situation quantitatively and objectively, IE techniques are indispensable. Management problems require unified companywide (and in some sense even subjective) judgments. However, such judgments must start from a correct understanding of the facts. The reason why IE techniques are used in productivity audits is that they are indispensable for providing a common understanding of the facts to all parties involved. The case study described in this chapter followed such logic; in Phase I a productivity audit was conducted and the productivity improvement program was drawn up. Then the improvement plan was implemented.

The Purpose of a Productivity Audit

Productivity audits are conducted so that productivity improvement activities may be undertaken and monitored based on statistical data. Accurate data derived from an audit also makes the following actions possible:

- Determine the target for productivity improvement.
- Select techniques for the introduction and control of the productivity improvement actions.
- Quantitatively forecast the potential for productivity improvement if the chosen techniques are applied.
- Draft the general plan for the productivity improvement project.
- Promote common “ownership” of the project (throughout the entire organization) based on a clear understanding of current problems, as disclosed in the audit report.

The audit is conducted in three parts: considering manufacturing methods (methods), work performance (performance), and application of resources (utilization). These three aspects of any business unit (abbreviated as MPU) are the three sources of productivity "losses," meaning levels of productivity that are lower that what could potentially be achieved. Specifically, we refer to

- *Methods losses:* excess labor hours or machine time required due to inefficient methods
- *Performance losses:* losses in potential productivity due to low performance of operators and/or equipment
- *Utilization losses:* losses derived from underutilization of labor and/or equipment

We will focus on the three areas of MPU, not only to identify losses, but also to seek improvements. The IE techniques applied in auditing (and later improving) each of these factors will be slightly different. In particular, regarding utilization, it is important to complete the audit, not only from the viewpoint of a simple calculation of a utilization ratio, but also considering opportunity losses (i.e., the creation of opportunity profit). For that reason, such things as the effectiveness of the quality assurance and maintenance systems must also be objects of the audit. Of course, the audit will also address all management levels involved in planning and control, including the production planning and control systems.

Audit Procedure

The procedure for an audit consists of five steps:

Step 1. Selection of the target area to be audited

Step 2. Identification of the MPU losses occurring in the current situation

Step 3. Study of the potential for making improvements and estimation of the increase in productivity that can be obtained

Step 4. Determination of the issues to be addressed by the productivity improvement project team

Step 5. Preparation of a master plan for productivity improvement

The purpose and general content of each step are as follows.

Step 1. Selection of the Target Area to Be Audited. Even in the case of surveying an entire factory, the characteristics of each manufacturing process are different, and the methods of auditing each process will therefore be different. Similarly, the procedures for achieving productivity improvement may be different in each area. For example, there are processes for which the simple productivity improvement yardsticks of *direct decrease in input* or *direct increase in output* are not appropriate. Likewise, there are workplaces that do not work at full capacity the entire time. Nevertheless, the results of the audit must be translated into a forecast of the potential for increasing productivity to enable the selection of control techniques to be applied.

How to connect the productivity improvement to overall business results must also be explained in the audit. Because of these complexities, to make the audit more manageable, the factory should be divided into several groups of processes, each called a *module.* By focusing on individual modules, it becomes easier to select the best audit technique for each and to estimate the potential for productivity improvement in each module. In the case of Company A, it was decided to divide the bathtub factory into 15 modules—for example:

Module A: mold coating

Module B: laminating

Module C: mold setting
Module D: actual molding
Module E: base assembly

Included among the modules were indirect areas, such as *repair of mold* or *warehousing of parts.*

Step 2. Identification of the MPU Losses Occurring Under the Current Situation. The existing situation is outlined quantitatively and objectively in this step. To be specific, an evaluation is made of how efficiently all applied resources (input), including personnel, equipment and machinery, and raw materials, are converted into output—finished products. As described in the previous section, productivity is divided into three factors—method, performance, and utilization (including planning and control)—based on the different IE techniques that are applied. For each factor, IE techniques such as work sampling and time studies are used to evaluate quantitatively and objectively the effectiveness of the applied resources in the existing situation and to determine where and to what degree MPU losses are occurring. The system for such audits is shown in Fig. 2.9.2, of which some additional explanation may be useful.

The Method Factor. The objective is to search for opportunities to raise the levels of the work standards. These standards may include the operating procedures, equipment, and machine setup conditions that have been accepted, as well as material-related standards based on the current design of the products. Accordingly, it is important not only to confirm

		Operator	Machine	Material
Method factor	Actions	•Confirm percentages for basic functions •Estimate the operator reduction factor	•Determine actual machine time •Estimate the potential for reduction of machine time	•Determine losses caused by product design •Estimate the potential (%) for improvement of yield
	Techniques	•Work sampling •Direct time study •Pitch diagrams •Human-machine charts •4W (what, who, why, where) charts	•Pitch diagrams •Sequence charts	•Design review •Value-added analysis
Performance factor	Actions	•Confirm present performance level •Estimate performance improvement potential (%)	•Confirm the facility performance •Estimate the potential (%) for improvement of performance	•Confirm the quality of materials and parts •Estimate potential for increasing first-pass yield
	Techniques	•MOST analysis •Direct time study •Output analysis	•Work sampling •Material analysis	•Yield analysis •Analysis of failure causes •Analysis of materials
Utilization factor	Actions	•Confirm utilization loss •Estimate the potential (%) for improvement of the utilization factor	•Confirm utilization loss •Estimate the potential (%) for improving utilization	•Confirm utilization loss •Estimate the potential (%) for improving utilization
	Techniques	•Analysis of setup procedures •Investigate the impact of staffing changes •Work sampling	•Downtime analysis •Work sampling •Analyze space utilization	•Scrap rate analysis •Inventory analysis •Investigate alternative materials

FIGURE 2.9.2 System for surveying the potential for improvement.

the losses resulting from the current situation, but also to endeavor to continue the audit activity far enough to estimate the amount of improvement potentially possible.

For example, in the case of evaluating a current situation with regard to labor productivity (see the Operator column in Fig. 2.9.2), the existing situation is clarified through the application of various techniques. The ratio of basic functions (work that directly contributes added value) is analyzed through work sampling, while time studies are performed to determine the extent of balance losses and interference losses. The results are presented in pitch diagrams or on human-machine charts.

The Performance Factor. The audit evaluates the extent to which established standards are adhered to. Not only the current performance level, but also the variation in performance (e.g., by the time of the day, between operators) is investigated, and the potential for improvement is estimated. Because a proper standard is normally available in examining labor productivity from the performance aspect, estimation of the potential for improvement can be done relatively easily by comparing actual operating time to the standard time (for example, analyzed by MOST®).

The Utilization (Planning and Control) Factor. Through direct observation, current nonconformities in regard to planning and control are investigated. Here it becomes necessary to carry the investigation further to estimate how much the profitability could be increased and productivity improved through a more effective management of the operation. The important thing, while working to understand the current situation, is to consider to what extent production time (utilization) could be increased through improved planning and control.

In production environments where labor productivity is the problem, it is important to clarify losses of all types (within the broad categories of M, P, and U) occurring under the current conditions. To do that, the appropriate methods must be applied: for example, work sampling to reveal the causes of line stoppages, or study of documentation and records to specify the impact of planning changes, trends in changeover and setup times, and so forth.

In the case study presented here as a concrete example, labor productivity was the main problem, but the audit procedure is not limited to such cases. Whatever the situation is, the primary methods used are those presented in Fig. 2.9.2.

Step 3. Study of the Potential for Making Improvements. Based on the findings in Step 2, the possibility for improvement is explored and the potential for productivity improvement is estimated. From a method aspect, the potential to reduce the applied labor or applied labor-hours is considered, while from the performance aspect, the potential for increasing earned value (output) is estimated. For planning and control, the possibility of increasing productive time is evaluated. Step 3 is almost an extension of Step 2, and the techniques illustrated in Fig. 2.9.2 will be applied in Step 3 as well.

Steps 4 and 5. Determination of the Issues to Be Addressed, and Preparation of a Master Plan for Productivity Improvement. Productivity improvement cannot be accomplished through use of just one IE technique. Therefore, in Step 4 the techniques that are to be emphasized in addressing each targeted problem are listed and tied into the master plan in Step 5. In Step 5, a program is planned for effectively solving the targeted problems and the system/organization for promoting the program is set up.

Case Study: Company A's Actual Situation and the Direction for Improvement Activities

Let us first consider how to proceed by mapping the present situation of a production area and how to determine from that the direction for the improvement activities. By examining the productivity improvement activities of Company A, it will be possible to see precisely what is involved in Step 2 of the audit procedure.

The Method Factor and Direction for Improvement. Figure 2.9.3 shows the results of the utilization analysis through work sampling. The average results for the 15 modules that were the subjects of the audit were 79 percent of the time in operation and 21 percent not in operation. Furthermore, the breakdown of the 79 percent was 32 percent basic functions (operations directly related to adding value) and 47 percent auxiliary functions (operations such as transportation or adjustment of test systems). Therefore, it was clearly revealed that under the present operating procedures, although operators were moving around a lot, little of the work was directly related to generating output, thus making the value of the labor low. Furthermore, to better understand the actual work methods being used, they were analyzed in detail using pitch diagrams (Fig. 2.9.4) and human-machine charts (Fig. 2.9.5.) In this way, M (method) losses associated with the existing operating procedures were made clear.

The Performance Factor and Estimation of the Potential for Enhancing Productivity. The potential for performance improvement was estimated based on (1) variation in output at different times of the day, and (2) comparison of standard times to actual times. Figure 2.9.6 shows the distribution of the performance level (standard time / actual time × 100 percent). The average for all modules is 76 percent, which shows that from the performance aspect alone (simply by having work accomplished according to standard times), there is the potential to improve productivity by 25 percent or more.

The Utilization (Planning and Control) Factor and Estimation of Potential for Enhancing Productivity. Productivity improvement through the planning and control is achieved by minimizing utilization losses by more effective planning, management, and control. For example, in the present case, when the results of work sampling were further analyzed, it was found that at the beginning of each shift, a waiting time equivalent to 6.6 percent of the available labor-hours was occurring. Furthermore, considering output by the time of the day (on the basis of a monthly average), it was confirmed that output for the 8:30 to 10:30 time period was low compared with other two-hour periods (Fig. 2.9.7). This U (utilization) loss could be prevented through better daily scheduling and improved allocation of personnel at the start of each shift.

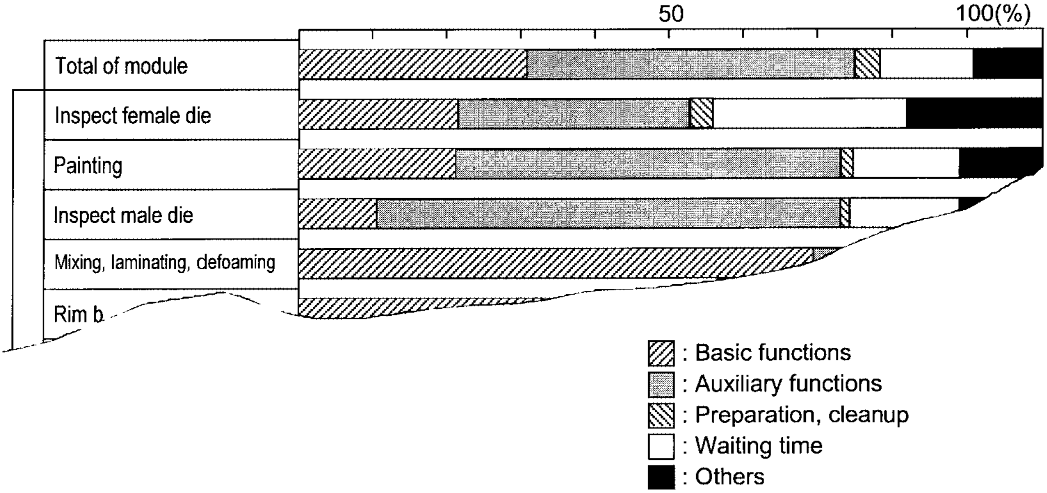
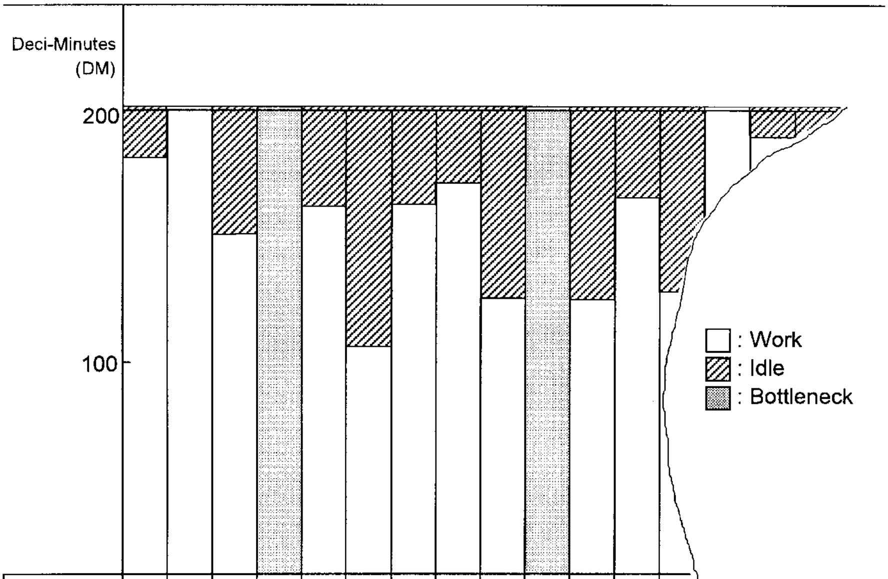


FIGURE 2.9.3 Utilization analysis through work sampling.

$$\text{Balance efficiency} = \frac{\text{Total work content}}{\text{Pitch time} \times \text{Number of operators}}$$

$$= \frac{11524.1}{200 x 94} = 61.3\%$$

Balance loss = 38.7%



Process step	Inspect mold	Painting	Inspect painting	Painting cure	Move die	Inspect die	Laminating	Holding rim	Laminate curing	Laminate curing	Paste sealing	Funnel set	Air perforating
Amount of work (labor DM)	700	1000	144	-	140	440	1717	168	125	-	126	136	101
Number of operators	4	5	(2) 1	-	1	5	11	1	1	-	1	1	1
Pitch time (DM)	175	200	144	200	140	88	156	168	125	200	126	136	

A pitch diagram recognizes the fact that a product can only pass through an assembly line at the rate determined by the bottleneck process. In this case, Painting, with a pitch time of 200 DM is one of three equal bottleneck processes. Thus, even if the person responsible for moving the die can do this in 140 DM, he or she must waste 60 DM waiting for the next product. The pitch diagram is used to identify all such waiting losses on a line and determine the total loss, which is called the *balance loss* and is expressed as a percent.

FIGURE 2.9.4 Pitch diagram.

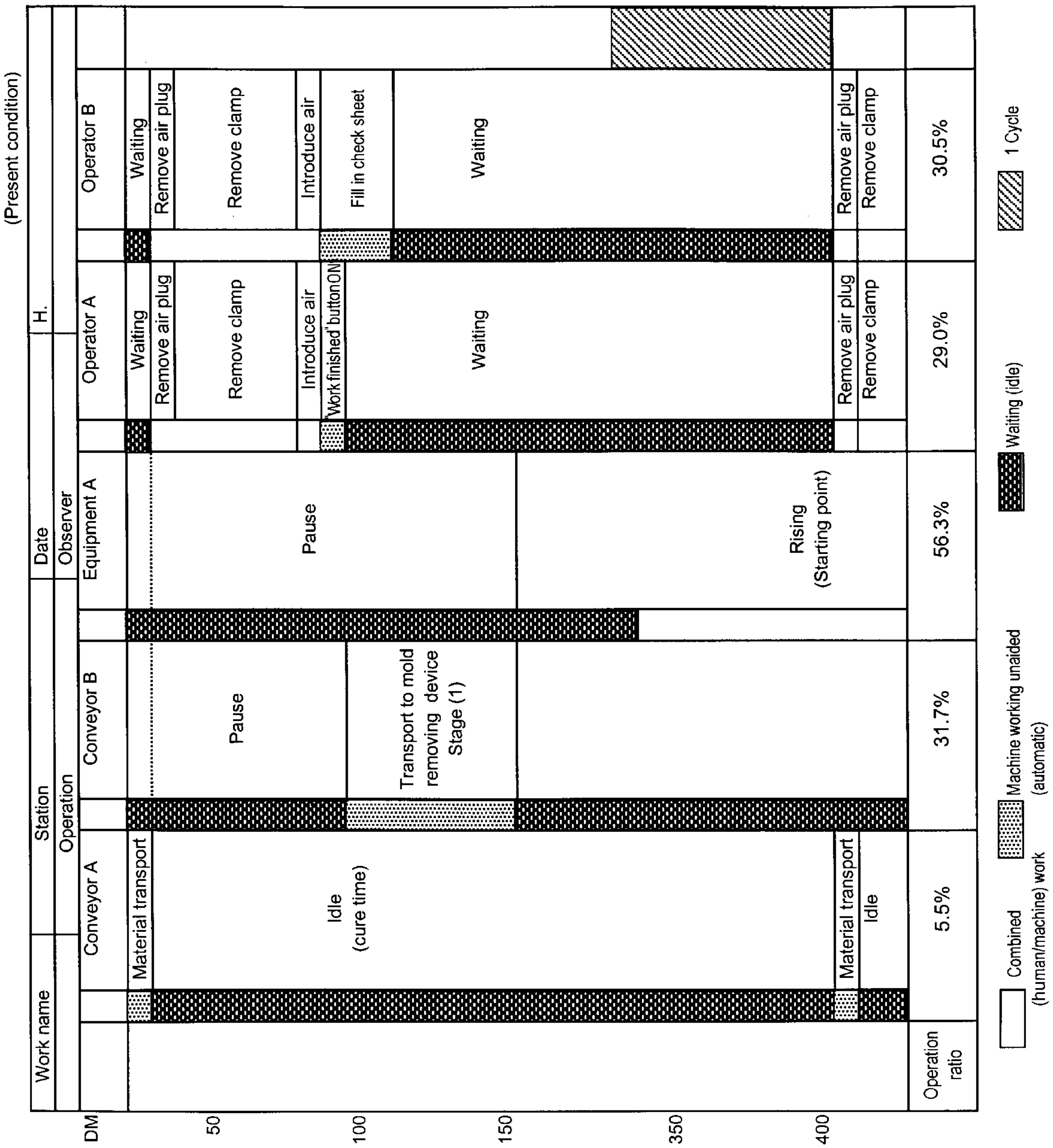


FIGURE 2.9.5 Human-machine chart.

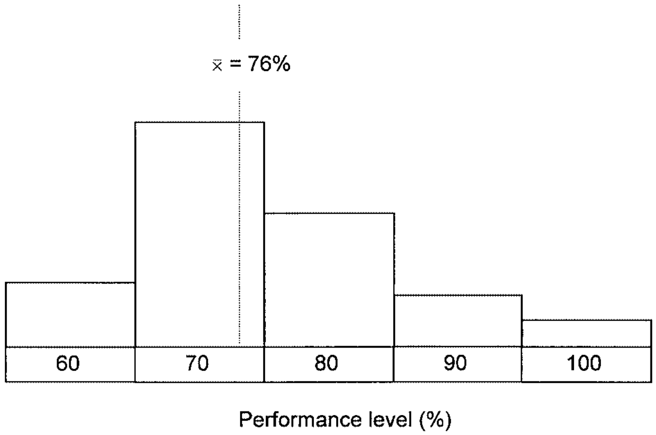
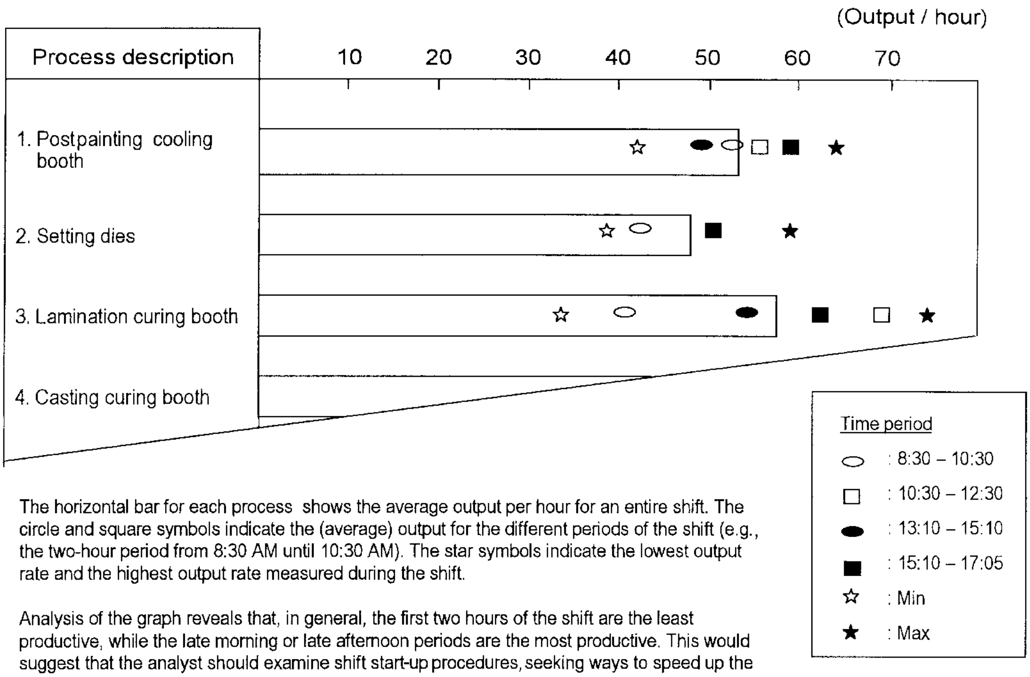


FIGURE 2.9.6 Performance level.



The horizontal bar for each process shows the average output per hour for an entire shift. The circle and square symbols indicate the (average) output for the different periods of the shift (e.g., the two-hour period from 8:30 AM until 10:30 AM). The star symbols indicate the lowest output rate and the highest output rate measured during the shift.

Analysis of the graph reveals that, in general, the first two hours of the shift are the least productive, while the late morning or late afternoon periods are the most productive. This would suggest that the analyst should examine shift start-up procedures, seeking ways to speed up the output.

FIGURE 2.9.7 Distribution of output by time period.

Case Study: Analysis of the Audit Results for Company A and the Creation of a Master Plan for Productivity Improvement

After the completion of the actual audit in Step 2, the audit results are organized and presented in a chart, and the project proceeds to Step 3: estimation of the potential for productivity improvement. For example, from the method aspect, the extent to which balance losses and interference losses can be reduced in each process is examined, and issues like what actions can be taken to raise the ratio of basic functions are studied. In making such estimates, a broad, global perspective for evaluation is necessary, which includes consideration of the possibility of actually achieving each possible improvement.

Figure 2.9.8 is the summary of the estimated potential for improvement for the case of Company A. Noting that the present case anticipates productivity improvements from all three MPU factors, methods, performance, and utilization, a total improvement potential of 63 percent was estimated according to Fig. 2.9.8.

Next, based on this estimate, one proceeds to Step 5: creation of the master plan for productivity improvement. Creation of the master plan includes preparation of a productivity improvement program and establishment of an organization for program management. In the case of Company A, productivity improvement proceeded in three steps. The purpose of Step 1 of phase II is reengineering of the production system, optimization of personnel allocation, improvement of daily work scheduling methods, layout improvement, optimization of inventory, enhancement of product yield, and so forth.

Step 2 is a bridge from Phase II to Phase III. In it, based on the content of the improvement actions planned in Step 1, a management system improvement program is woven in, addressing issues such as building a solid production planning and control system, improving the efficiency of indirect management groups, and creating a productivity control system. Finally in Step 3, which corresponds to Phase III, a more efficient integration of the sales and manufacturing functions is explored.

Figure 2.9.9 shows the system for conducting and managing the project. With projects of this kind, the functions that each employee is to perform must be made very clear, not only for the staff, but also for the managers and frontline supervisors.

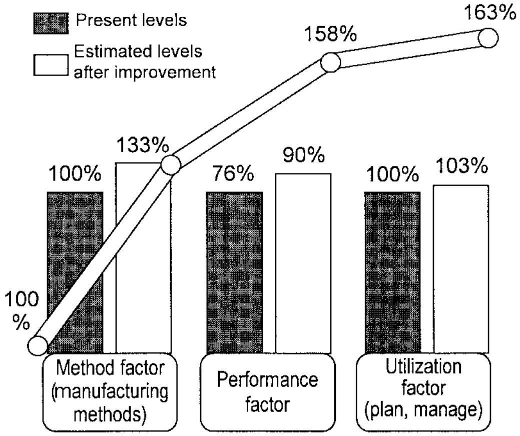


FIGURE 2.9.8 Estimation of total productivity improvement.

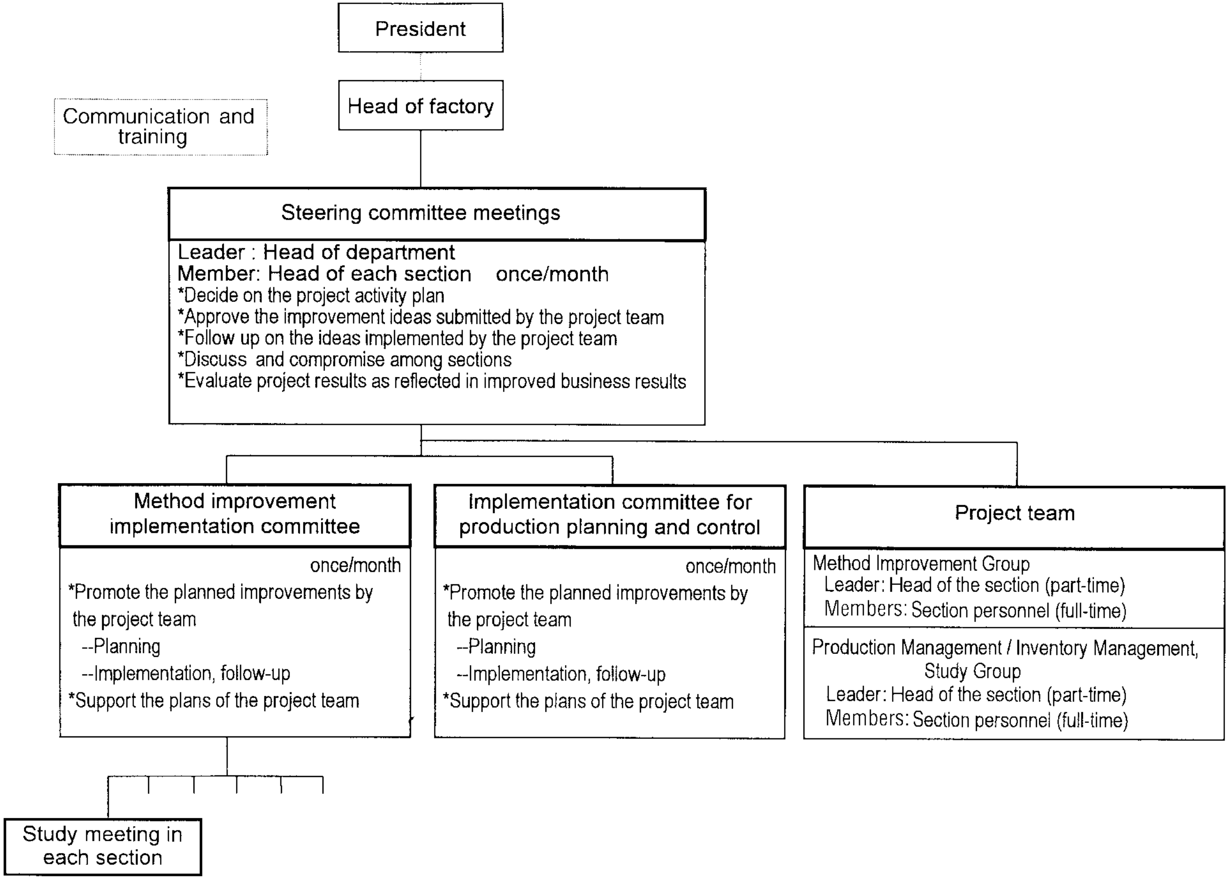

President
Head of factory
Communication and training
Steering committee meetings
Leader : Head of department
Member: Head of each section once/month
*Decide on the project activity plan
*Approve the improvement ideas submitted by the project team
*Follow up on the ideas implemented by the project team
*Discuss and compromise among sections
*Evaluate project results as reflected in improved business results
Method improvement implementation committee
once/month
*Promote the planned improvements by the project team
--Planning
--Implementation, follow-up
*Support the plans of the project team
Implementation committee for production planning and control
once/month
*Promote the planned improvements by the project team
--Planning
--Implementation, follow-up
*Support the plans of the project team
Project team
Method Improvement Group
Leader: Head of the section (part-time)
Members: Section personnel (full-time)
Production Management / Inventory Management, Study Group
Leader: Head of the section (part-time)
Members: Section personnel (full-time)
Study meeting in each section

FIGURE 2.9.9 Project organization.

AN ACTUAL EXAMPLE OF IMPROVEMENT ACTIVITY (PHASE II)

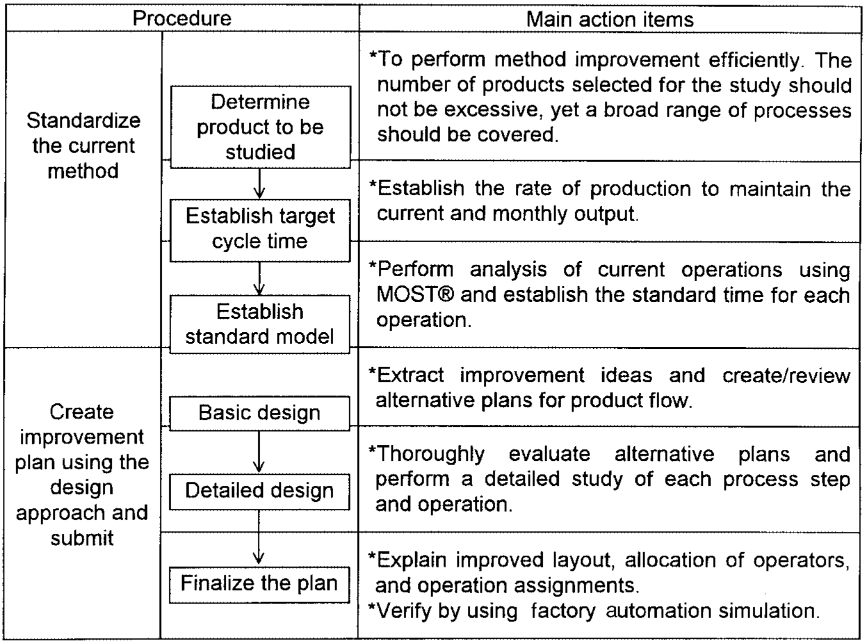
The purpose of Phase II of the productivity improvement activities at Company A was reengineering of the production system. It consisted of three labor productivity improvement projects that were conducted in parallel: (1) optimization of personnel allocation, (2) creation of a solid planning and support system through improved scheduling (implementation of short interval scheduling), and (3) improvement of work-in-process inventory between process steps (calculation of stock points and optimum inventory levels).

Each of these projects is deeply related to the others. In this section we will focus on how Company A implemented optimization of personnel allocation. This activity consisted of allocating personnel in response to a given workload and was applied in this case to achieve improvements from the method factor as part of a design approach. The major steps are shown in Fig. 2.9.10.

As a result of conducting various method improvements, an assembly line whose structure prior to improvement required 30 operators, could be run with 15 persons. The major improvements accomplished were

- Reduction in the labor required for material handling through introduction of automated material transfer methods and a shortening of the line
- Improvement in efficiency through better organization—specifically, re-layout of each workstation and reallocation of work
- Improvement of jigs, fixtures, and tools and changes to work methods

In parallel with these method improvements, scheduling improvements and reduction in work-in-process inventory were also accomplished. Overall, work that required 171 people prior to the improvements could now be accomplished with 133 people (personnel reduction effect: 28



Procedure		Main action items
Standardize the current method	Determine product to be studied	*To perform method improvement efficiently. The number of products selected for the study should not be excessive, yet a broad range of processes should be covered.
	Establish target cycle time	*Establish the rate of production to maintain the current and monthly output.
	Establish standard model	*Perform analysis of current operations using MOST® and establish the standard time for each operation.
Create improvement plan using the design approach and submit	Basic design	*Extract improvement ideas and create/review alternative plans for product flow.
	Detailed design	*Thoroughly evaluate alternative plans and perform a detailed study of each process step and operation.
	Finalize the plan	*Explain improved layout, allocation of operators, and operation assignments. *Verify by using factory automation simulation.

FIGURE 2.9.10 Procedure for method improvement.

percent). In addition, cycle time reduction was also accomplished (cycle time reduction effect: 7 percent). Thus, over a one-year project, a total productivity improvement of 38 percent was accomplished for this one assembly line, focusing on the method factor alone.

The procedures for achieving method improvements have been shown in Fig. 2.9.10. Whether applied to the standardization of existing methods, development of an improvement plan, or a concrete plan implementation, all the methods used are basic IE techniques. For example, in the standardization of existing methods, the first step is a clarification of the procedure for each operation, followed by the standardization of those procedures and the standardization of time values using techniques such as MOST. Also, to generate improvement ideas, it is important to make effective use of IE techniques such as line balancing and determination of interference between operators and equipment through application of human-machine and machine-machine charts. While there is insufficient space in this chapter to describe each IE method or technique, we trust that the value of IE techniques when used in productivity audits and applied to productivity improvement activities has been made clear.

SUMMARY

In the current business environment, there is a never-ending escalation of customer needs; customers continue to demand improvements in cost, delivery, and quality. Consequently, in manufacturing situations, a continuous review of how work is done and how it can be improved is a subject of high priority. Use of new technology and application of automation and mechanization are indispensable for productivity improvement. However, correctly evaluating the existing production situation and proceeding to improve it through better methods and management are also important. To accomplish such activities, the effective application of IE techniques can play a key role, both in productivity audits and in making significant productivity improvements.

BIOGRAPHY

Shoichi Saito is a member of the board of directors of Japan Management Association (JMA) Consultants in Tokyo. He was born in Nagano Prefecture and received his bachelor's degree from Tokyo Rika (science) University in 1971. He joined JMA Consultants (JMAC) that year and became a senior consultant in 1989. His consulting work covers all aspects of productivity improvement, particularly management-related issues. He is an authority on methods engineering, work measurement, and other industrial engineering techniques and has worked on the development of several productivity-related tools that are now offered by JMAC. He is also active in the field of office productivity and is the coauthor of *A Practical Manual of Office Productivity Techniques* (in Japanese).

Source: MAYNARD'S INDUSTRIAL ENGINEERING HANDBOOK

CHAPTER 2.10

CASE STUDY: PRACTICAL TEAMWORKING AS A CONTRIBUTOR TO GLOBAL SUCCESS

Bob Bell
Michelin Pioneering Consultancy Group
Stoke-on-Trent, United Kingdom

Teamworking has become a vital component in the success of many large organizations today. The approach and success of teamworking as illustrated in this chapter is drawn from Michelin's U.K. experience and is only one illustration of similar experiences throughout the Michelin International Group. In the U.K.'s case, change and progress through teamworking was born out of necessity and subsequently has become an essential way of working. It would be wrong to give the impression that external factors had not contributed to the achievements within the company. Indeed, a mini-industrial revolution, which was taking place in the United Kingdom, was an important support in creating a more receptive climate. Nevertheless, Michelin was in the vanguard as a champion of change rather than being a follower.

INTRODUCTION

Michelin's global importance in the world tire market has grown out of its technical superiority, its ability to provide leading-edge solutions to its customers' requirements, and its continued recognition that success is dependent upon the commitment and contribution of its employees. The history of the company from its inception in Clermont-Ferrand, France in 1889, demonstrates that, through people, the company's name has become synonymous with quality. Michelin became a household name throughout the world ably assisted by Bibendum, the Michelin logo, which has been in existence over 100 years. As the logo has evolved, there has been a progressive slimming that symbolizes the continuous dynamism of the company. Sustained success has been nurtured through adapting the company's management style, thus ensuring harmony between technical innovation and the essential contribution of its employees.

BACKGROUND

In the United Kingdom, Michelin registered its first commercial operation in 1905, and the first factory was built in 1927. The development of the U.K. manufacturing operation followed the fortunes of the automotive industry and, as with other tire manufacturers, there was an accelerated growth of manufacturing units in the 1960s. However, by the late 1970s, there was a forced rationalization in line with the demise of the U.K.'s automotive operations. The trend only changed as far as the domestic market was concerned with the arrival of Japanese implants from the mid-1980s onward. The fact that the Japanese chose the United Kingdom as a springboard for their supply needs in Europe was a clear indication that British industrial relations had substantially changed. What contributed to this will be discussed later.

To fully understand what has been achieved and to draw value from it, one needs to better understand the company's background. The organization of the manufacturing workplace throughout Michelin was largely influenced by Taylorism over many years. Industrial engineering techniques were used to specify both output potential and workplace design. Employees were encouraged to improve and sustain their productivity by bonus payment systems. This policy contributed to the company's success for many years. However, to sustain payment systems required a lot of industrial engineering time. Although payment studies were very accurate in themselves, the actual realization of results was not achieved so precisely, and the study method became, in a sense, counterproductive. Also, needs and motivations began to change, perhaps imperceptibly at first, on the part of both employees and management alike. Negative behavior and attitudes that had manifested themselves in collective stances were growing. These tendencies rose to epidemic proportions throughout British industry in the 1970s. Managers probably rationalized the cause as a purely negative trade unionism and reacted accordingly. They were slow to recognize that the underlying needs of employees were changing, also at an accelerating pace. In fact, those needs were to bring employees and their contribution closer to the business needs.

CHANGING WORKPLACE ENVIRONMENT

Employees had been given little on which to develop a sense of responsibility, and the external culture did nothing to encourage the employees to take responsibility in the first place. They focused only on personal needs, with little concern for the company's overall requirements to satisfy the increasing demands of the customer. Fox recognized as early as 1966 that to change behavior one must change the role of the worker, and to do this the workplace environment can be an important determinant [1]. In considering the environment, one needs to consider various aspects. The management structure had been designed to supervise and direct rather than to trust, coach, and counsel. This created a control and blame culture rather than one that encouraged innovation and employee involvement. Clearly, from this standpoint, it was going to be necessary to change managers' views as well as those of the employees. This required a reappraisal of both manager and employee expectations in the workplace and the encouragement of more demanding and exciting horizons.

At this juncture, it is appropriate to reflect on the fact that the workplace evolution has been a function of social history. While it is not necessarily clear whether change in behaviors and attitudes were determined within the workplace, there is little doubt that World War II impacted the industrial relations scene in Britain during the 1960s and 1970s. Unemployment and disillusionment provided a working environment in which reactionary trade unionism could grow. Unfortunately, the consequence of this type of employee representation and organization only further contributed to the negative economic spiral with its by-product of increased unemployment.

In this reactionary and combative environment, it was difficult for both employees and management to see how to establish a positive future in which trust between the parties could be established.

There was no doubt that the population at large wanted change because it began to realize the fortunes of Britain and its global importance was being undermined by failure to handle ever-decreasing negative economic cycles. A major factor was its industrial relations reputation, which was fast becoming the worst in the world.

NEW ECONOMIC DEMANDS

A catalyst for this change was certainly needed, and this took the form of Thatcherism—a radical and aggressive approach that, while having both positive and negative features, did establish the foundation for today's economic success. With it came the marginalization of the more radical elements of the trade union movement and the emergence of more positive approaches, which first appeared in the large engineering unions. Progressively a number of trade union leaders began to believe that greater weight needed to be given to teamwork, motivation, and commitment to achieve success and job security. The "new agenda" devised by the General Municipal and Boilermakers Union (GMB) and Communications Workers Union (CWU) promoted this theme and the importance of management and workers working together to achieve prosperity [2]. Thatcherism, therefore, of the 1980s served as the rebirth of Britain as a viable and vibrant business nation.

In the meantime, the world had been moving fast and globalization of markets placed new economic demands on business. The need to increase the rate of productivity improvement, to de-layer management structures, and to create flexible contracts all became the challenges of the 1990s. The impact on the "psychological contract" between employer and employee has not yet been fully understood, nor has its consequential influence on employee relations and motivation in the future. These are all issues that have colored thinking in Michelin toward establishing the right balance between short-term and medium/long-term actions and strategies.

Pressure on manufacturing costs highlighted the need to operate differently. Previous emphasis on bonus payments placed emphasis on inspection rather than built-in quality. Industrial engineering studies contributed to de-skilling rather than "responsibilizing" employees with the result that employees became mentally underemployed. The mentality of doing only what was specific to the job was becoming a barrier to achieving the future demands of the business. It is interesting to note that neither the needs of the individual nor the company were being fully met. Employees were not stimulated to use the extent of their potential, although, if asked, many would probably have shown only limited interest in the possibilities. Time and tradition conditioned them to believe their responsibility was limited by design, and there was little need or interest in them doing more. It was clear, however, that if properly handled, a win/win could be achieved.

To illustrate what would have been regarded as normal in the 1970s and early 1980s, consider the launch of an industrial engineering study. There was little or no involvement of the "experts," the employees, who were going to be affected. The industrial engineer would carry out the study with minimal contact, jealously guarding any understanding of techniques used. When the study was complete, a proposal presentation was made, often to an employee representative. Then began the problem of persuading people to accept the change. Often, successful implementation was in some way diluted to gain final acceptance.

EMPLOYEE INVOLVEMENT PROGRAM

What then is Michelin in the United Kingdom? Having opened its first manufacturing site in Stoke-on-Trent in 1927, it has emerged with four sites today and exports a high percentage of the car and truck tires produced. Previously, with six manufacturing sites, it was very dependent on domestic sales, but the major rationalization of the British car industry in the 1970s and early 1980s had an impact on all U.K. tire manufacturers, and Michelin's response was to focus increasingly on global markets. This meant rationalization and successful restructuring of its manufacturing base into four manufacturing units. To be successful in the export market necessitated a significant improvement in manufacturing cost prices, and it was clearly understood that this could only be achieved through the full involvement of all employees.

The first real progress in enlisting the involvement of employees was to arise from small beginnings when in 1981 the first problem solving groups (quality circles) were started with volunteers at the Ballymena, Northern Ireland factory. The success of this initiative, which impacted the U.K. sites and further afield in Michelin, was based on an early understanding that the people could only be fully involved in problem solving if they were properly trained in problem-solving techniques. It is notable that Purcell et al. [3] found in a study of 140 companies that foreign-owned companies "appear to be more advanced in their adoption of modern Human Resource Management techniques" than their British counterparts. The voluntary nature of Michelin's approach to quality circles has been the key to their success. As Dale [4] found from his study of British quality circles in 1985, the imposition of a quality circle program may contribute to its ultimate failure and therefore should be avoided. With a proper piloting of the experience in Ballymena and an improved understanding of the practicalities and value of such a mechanism, the program was extended over a number of years to all the other manufacturing sites.

Experience showed that creating an enthusiasm for involvement and problem solving was relatively easy. However, to sustain problem-solving activity required the use of appropriate techniques. First, this avoids the real risk that efforts are focused on finding a solution before the real causes are understood. Moreover, the use of techniques also helps to minimize another pitfall, that of believing too much in oneself. This tendency became apparent once a team had successfully solved one or two problems. At this point, there was the natural temptation to take shortcuts, believing that certain methodical steps were not necessary. Insistence on the part of the facilitator on proper use of techniques handled this issue effectively. As teams handled increasingly difficult problems, again, the proper use of techniques stopped the team from being outfaced by the problem.

The experience gained at this juncture provided a realization that the involvement of people in the business was a professional challenge and not just an easy option. What was being sought was how to achieve employee commitment. Etzoni defines commitment as positive involvement with the opposite being a manifestation of intense negative orientation, which he defined as alienation [5]. Commitment is generated by appropriate application of power by management but also when the decisions mirror the needs of the individual. In contrast, alienation is created both by illegitimate use of power and by frustration of wishes, needs, and desires of the individual. Therefore, it may be argued that the degree of involvement has a direct influence on the employees' level of commitment. Etzoni does, however, point out that the involvement can be affected by external factors such as trade union membership, basic value commitments, and the personality structure of the participants. The latter may explain management's emphasis on cultural change. In any case, it soon became obvious that commitment alone would not be enough. Employees needed to sustain a high level of competence, and this necessitated effective training. Recognizing the increased pace and level of demands together caused a focus on the fact that employees needed to have a capacity for change. This challenge, as it became better understood, opened up a whole range of opportunities that has fundamentally changed relationships and responsibilities of Michelin people today.

Nothing can be achieved in isolation. So, while experience was being developed in involving employees in problem solving and improvement team activities, shift patterns were being extended to the seven-day work week and production years were extended progressively from 228 days to 357 days. This was all being achieved in a context of reducing labor and costs.

Another factor that could not be underestimated was that with reduced labor there was a heightened interdependence on each employee. In a nutshell, the company was involved in a transformation of its operations and as such was increasingly dependent on the total contribution of each and every employee.

INCREASED EMPLOYEE RESPONSIBILITY

In what way can one illustrate the change in approach? Let us return to the industrial engineering study example. The approach was now totally different. First, if a study is to be carried out, those who could be affected are informed, encouraged to contribute ideas (through brainstorming for example), and asked to comment during the study. This ensures that the final solution can have a level of local ownership in its design, and the implementation can have a successful impact.

When actual workplace design is under consideration, the study process is reversed so that as many interventions on issues that affect the workplace as can be practically handled by the employee are designed in, thus increasing responsibility and/or control of the operation (see Fig. 2.10.1). Productivity is considered at section or department levels rather than at the workplace level so that solutions may be fully integrated and effective. With this approach, the business need is achieved while increasing the workplace responsibility and, therefore, the satisfaction of the individual employee.

An involvement strategy is difficult to implement because it requires a strong element of trust on the part of management and individual alike. Having encouraged employees to step forward and participate, there is no going back as all credibility would be lost and future attempts would be treated with suspicion and distaste. Managers and employees have to learn to approach work issues in a different manner. For the manager, there needs to be a complete reappraisal of the role and the number of levels in the hierarchy. The range of competencies needed is different. Managers need to use leadership skills more subtly so that the emphasis is on coaching and facilitating rather than on directing and supervising. For employees given scope to act and take decisions, there is a whole new learning process to be achieved. Added to this is the need for each party to perceive the other differently so that two-way trust and respect can provide a basis for sustainable success. While it may seem that one is putting too much emphasis on seemingly soft issues, their achievement is crucial to the overall goal. In the case of Michelin U.K., the involvement strategy developed over time, and it would be untrue to give the impression that all the issues were understood at the outset. There were, however, some principles which proved fundamental and helped to create a foundation for success. First, there was a clear intention to involve employees and invest the time and resources nec-

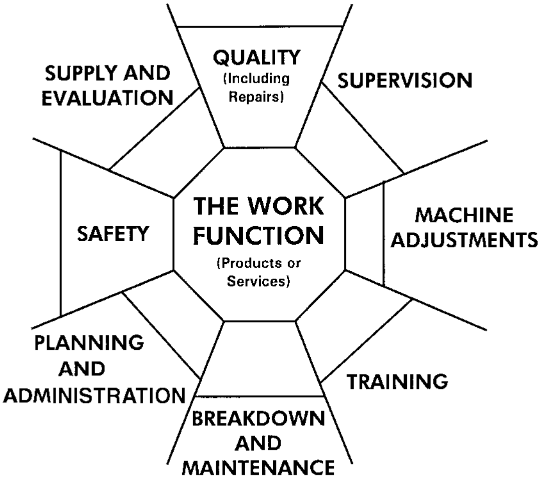

QUALITY (Including Repairs)
SUPPLY AND EVALUATION
SUPERVISION
SAFETY
THE WORK FUNCTION (Products or Services)
MACHINE ADJUSTMENTS
PLANNING AND ADMINISTRATION
TRAINING
BREAKDOWN AND MAINTENANCE

FIGURE 2.10.1 Developed workplace organization.

essary to ensure the environment was right for success. There was also a determination to convince individuals and not to be dissuaded by any negative stance, particularly of a collective nature. The latter was very important because too often in the past managers had compromised peace and in doing so only contributed to a slow deterioration in the fortunes of the business. This determination should not be misinterpreted as being dictatorial. Persuasion was in effect the new order. This claimed a lot of time, patience, and effective communication. An essential feature was clear senior management commitment, which had to be regularly demonstrated, such as through frequent participation in presentations. This was essential to ensure no perceived or real barriers developed in middle management ranks.

But the key to Michelin's success, as mentioned earlier, was that team activities were introduced initially on a voluntary basis, piloted so as to understand their dynamics before being progressively extended. This extension depended upon the time required to ensure that both employees and management had learned to cope with this new way of working. When this was achieved and the elements for success understood, the next step of spreading the impact and success was much easier to achieve.

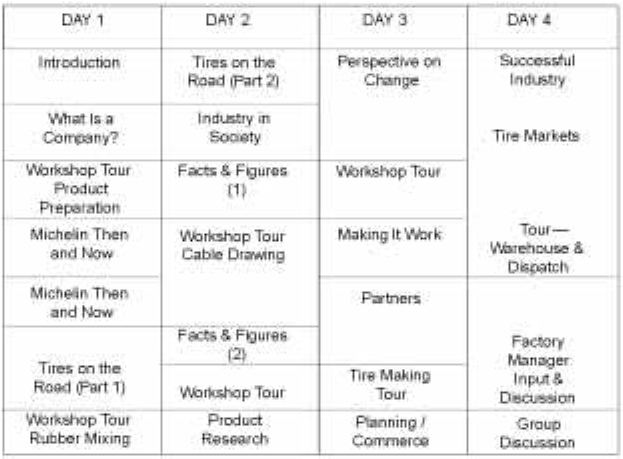
One must at this point return to the underlying question, why change the structures, responsibilities, and style of management? There was no doubt that traditional forms of management and employee working made the company a world leader. But this very fact was the prime motivator for change. The company and those who work in it were motivated to assure the company's future and to do this in increasingly competitive markets. All the resources required had to be marshaled differently to meet both technical and economic constraints. In this context, constraints became positive challenges rather than demotivators.

So what has been achieved since the early introduction of quality circles? Obviously, improvement teams in a whole range of guises have become integral to the way Michelin handles continuous improvement in its business. While employee satisfaction was greatly enhanced, as was the experience for many companies that introduced quality circle programs, see the Collard and Dale [6] study of 132 manufacturing companies, which found that for Michelin, employee satisfaction was only one aspect of the perceived gains. More important, the experience highlighted to the company the exciting potential available in terms of effective involvement of human resources. This was certain to make such a major contribution to its long-term future.

To build on this involvement opportunity, it was necessary to ensure that employees understood the business context. Coming from an era when Michelin's reputation was firmly established on the development of the radial tire and technical superiority, it would have been easy for both management and employees to develop a level of complacency, even arrogance. But the reality was that as our patents ran out and the opposition launched its competitive response, any cushion or lead that Michelin had was soon reduced.

EFFECTIVE COMMUNICATIONS—KNOW YOUR COMPANY

For Michelin employees, the most certain element in our business was that it had to evolve and change. The things to be achieved had to be done faster, better, smarter, and with less costs. As in many established industries, the negative aspects of demarcations had existed not only within functions but also between functions. Effectively communicating this fact was a challenge in itself. Early efforts to establish an effective communication structure did deliver some progress, but difficulties were also experienced. A policy of monthly team meetings was established with managers and team leaders trained to facilitate the meetings. In our enthusiasm to make the meetings effective, briefing information was supplied that covered all corporate activity. With this level of support, the tendency was (particularly for the weaker leaders) to use all of this information whether the content was perceived to be relevant for the actual team or not. In these cases, the meetings became briefings rather than a two-way exchange of views and information. Progress has, of course, been made from those early experiences; the corporate input is only that which is essential and should only absorb a small portion of the meeting's time. More important



DAY 1	DAY 2	DAY 3	DAY 4
Introduction	Tires on the Road (Part 2)	Perspective on Change	Successful Industry
What Is a Company?	Industry in Society		Tire Markets
Workshop Tour Product Preparation	Facts & Figures (1)	Workshop Tour	
Michelin Then and Now	Workshop Tour Cable Drawing	Making It Work	Tour—Warehouse & Dispatch
Michelin Then and Now		Partners	Factory Manager Input & Discussion
Tires on the Road (Part 1)	Facts & Figures (2)		
	Workshop Tour	Tire Making Tour	
Workshop Tour Rubber Mixing	Product Research	Planning / Commerce	Group Discussion

FIGURE 2.10.2 Practical example of Know Your Company program.

is the opportunity to exchange ideas and views on the team's activities and how these can contribute better to the overall business objectives. The team meeting has as its objectives to enhance understanding, encourage involvement, and resolve problems. Today, various parts of the organization have followed the experience of nominating team members who take responsibility for interfacing with management on a specialist area such as production, quality, or safety.

Another difficulty (which should have been obvious) was the importance of communicating in a language and in concepts that all could understand. Typically, the language of management was either not understood or misinterpreted at various levels. Having recognized the problem, it was obvious that this could undermine the effectiveness of communication with the resultant negative impact on progress. The solution, which was pivotal to progress, was the development of a discovery learning program for all employees at all levels known as "Know Your Company." This entailed 3 days off-the-job in seminars and practical sessions learning about the context of the company's business, the markets, and concepts such as profit, depreciation, and capital investment. All was delivered or discovered at the pace and in the language that each small group (typically twelve in a session) of individuals understood. This implies that the language used may have differed depending on the level of employees in the session. Also equally important was that this program was company-wide because there was then a learning opportunity for all. Senior management was fully implicated in the final day's question and answer session so that employees could meet, listen to, and discuss with senior management their concerns and dissatisfactions face-to-face.

Whereas this was a major investment, it illustrated the value of improving the overall understanding of our employees. Giving employees a vision of the future evolution and the "why" improved their feeling of belonging and being trusted, which in turn provided a basis for further progress. Even when employees may not have liked what they heard, there was the opportunity for debate well in advance of any necessary action. Today, employees are regularly updated regarding the context of the business need so that misunderstanding is not a barrier to further progress.

In any teamworking environment, there is the risk of losing the effectiveness of the individual within the achievement of the team. This is not always accepted by promoters of team concepts but consider, in any walk of life, where do you find team excellence without each team member playing his or her part to the best of his or her ability? This does not mean that they must all be "stars," but their individual effort and level of competence blends to achieve the result. In recognizing the importance of this issue in Michelin, considerable effort has been focused on regular individual performance reviews and annual appraisals. Aspects that form part of the review are listed in Fig. 2.10.3.

- Documentation
- Conformance Controls
- Productivity
- Quality
- General Housekeeping
- Safety
- Attendance
- Flexibility
- Teamwork
- Post development
- Initiative
- Knowledge validation
- Overall commitment

FIGURE 2.10.3 Content of performance reviews.

INDIVIDUAL TEAM MEMBER ROLES

Figure 2.10.4 illustrates the important relationship between the role as an individual and the role as a team member. Training and regular validation has been used to assure the adequacy stage so the employee is competent to carry out the responsibilities for that which he or she is employed. But this is not enough. The application of competence cannot just be relied on and, more important, improvement cannot be assured without regular performance reviews and objective setting. The other side of the diagram illustrates that, as a team member, involvement in improvement team activity and team meeting was facilitated. In the background, the Know Your Company input was used to update the context. There is no doubt that understanding the importance of the combination of the two roles provided an important step toward further de-layering and self-supervised teams.

SELF-SUPERVISED TEAMS

The major teamworking breakthrough was the development and widespread evolution of the self-managed team concept. (In Michelin, we believe *self-supervised* is more appropriate than self-managed because to have true management responsibility, employees need to have a full understanding of the business.) This concerned the creation of work *cells.* In this context, the cell is a team of employees which has the ownership, responsibility, authority, and accountability for everything it does. The members supervise themselves when dealing with daily work demands and assuring the delivery of quality products. A cell may have a number of employees from each shift working on the same workplace, or there may be individual cells on each shift whose work is coordinated by a cell manager responsible for performance review, future planning, and so on. Apart from this responsibility, the role of the cell manager is best defined as

- Providing cell members with the means and the environment to achieve business goals
- Coaching and developing individuals and the team how to achieve these goals, which include ongoing improvement
- Remaining accountable for overall cell performance

As a principle, the creation of an official team leader has been discouraged, as this step would only recreate an additional layer of management and undermine the increased responsibility of the team members. Should the team want to recognize a need for a decision maker, then this role is rotated to assure the ability of the team to operate in spite of any absence. If the leadership role was focused on one individual, then, in the absence of that individual, the performance of the team would be put at risk.

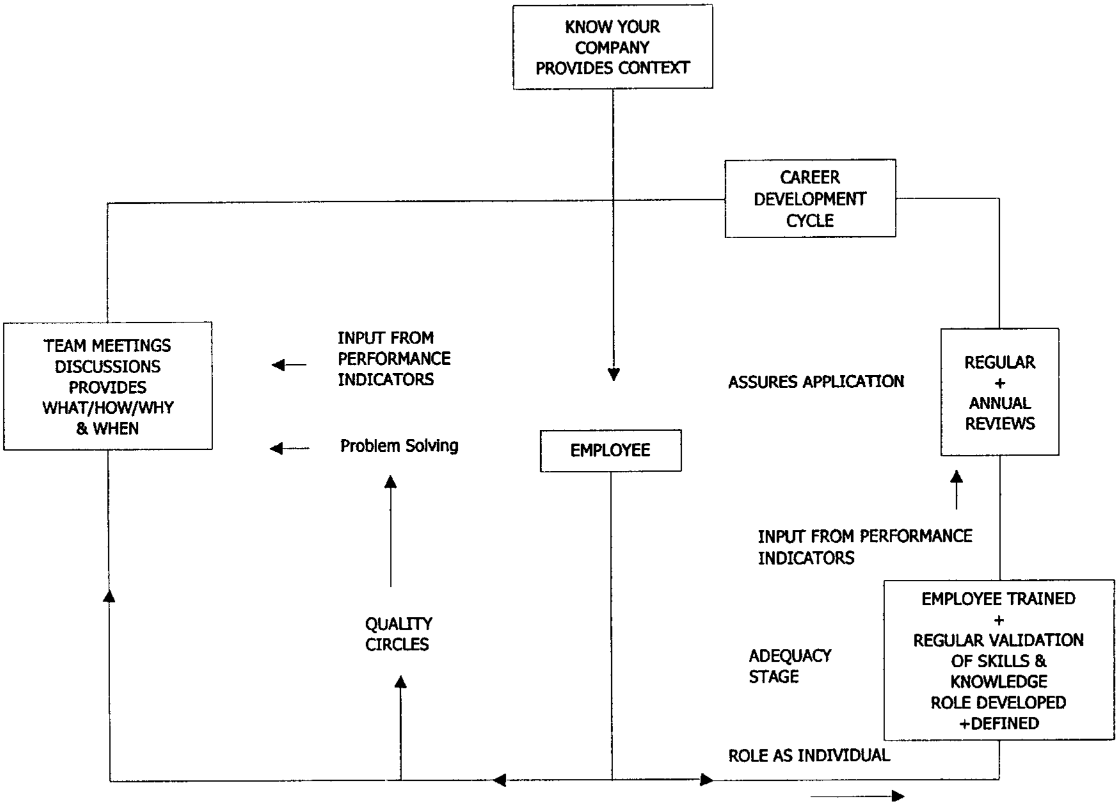

KNOW YOUR COMPANY PROVIDES CONTEXT
CAREER DEVELOPMENT CYCLE
TEAM MEETINGS DISCUSSIONS PROVIDES WHAT/HOW/WHY & WHEN
INPUT FROM PERFORMANCE INDICATORS
Problem Solving
ASSURES APPLICATION
REGULAR + ANNUAL REVIEWS
EMPLOYEE
INPUT FROM PERFORMANCE INDICATORS
QUALITY CIRCLES
ADEQUACY STAGE
EMPLOYEE TRAINED + REGULAR VALIDATION OF SKILLS & KNOWLEDGE ROLE DEVELOPED +DEFINED
ROLE AS INDIVIDUAL

FIGURE 2.10.4 Relationship between the role as an individual and the role as a team member.

In a cell operation, the importance of team members cannot be emphasized enough because they have to be professionals in their own right. In a product such as a tire, it is vital that team members are competent to recognize and deal with the "known," normal problems that arise. More important, they must recognize the unknown and know the expert to contact for instructions . . . even in the middle of the night should a problem arise. There is an important level of trust that must be developed because the employee must not be tempted to take his or her own initiative in this case. To develop the team further, one can then train team members to recognize and handle the lesser-known problems, thus widening their level of expertise.

Essentially, management has to have confidence in the team, allowing it to deal with day-to-day problems and to work flexibly. It is the cell manager's job to encourage further improvements, provide procedural documents, and support training and validation actions. The role of the cell manager in regular performance reviews closes the feedback loop, thus assuring sustained and improved achievement.

SELF-DEVELOPMENT CENTERS

The elements that contributed most toward teamworking are named in the bulleted list. As work progressed, the appetites of employees were also aroused for individual development.

Self-development centers were introduced to satisfy this need. What became clear was that those who involved themselves in self-development were, as a result, better able to handle the various demands of change as they arose. This justified setting up self-development centers at each manufacturing site to include

- Total quality management
- Improvement teams and quality circles
- Redefinition of training and annual validation
- Performance reviews
- Development of the production and engineering roles
- Know Your Company courses
- Self-development centers

During the evolution of change, it became apparent that there were other barriers or challenges that existed with the potential to undermine the very culture that was being created. It was necessary to take action on a number of fronts and this included reviewing, changing, or in some cases, eliminating

- Job descriptions
- Clocking in*
- Overtime payments*
- Working hours and flexibility
- Payment systems
- Them and us attitudes*
- Traditional ways of working*
- Management demarcation*

REWARDING TEAMS

Unlike other organizations, Michelin U.K. does not have special names for improvement teams. The recognition of achievement and contribution are regarded as important, but monetary reward is not considered appropriate. Various methods of recognition have been used including team challenges, presenting experiences to other organizations and visits and participating in national forums such as the National Society for Quality through Teamwork. This society, while mainly supporting teamwork activities in the United Kingdom and Ireland, also has overseas members.

CONCLUSION

At the outset, it is unlikely that Michelin management's vision of the full potential of teamwork was as acute as it is today. After years of experience, there are still surprises regarding the progress that can be achieved. However, from the beginning what was clear was a desire to first improve individual effort and then integrate this into team achievement. Combined

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Those marked with an asterisk have been eliminated.

CASE STUDY: PRACTICAL TEAMWORKING AS A CONTRIBUTOR TO GLOBAL SUCCESS

with this was the intention to encourage employees to use their knowledge and experience to make improvements in their workplace. This was to benefit both themselves and the business. In practical terms, the company wanted to create an environment from which progress could emanate. When trying to establish a vision for change, it is rarely feasible to imagine all the possibilities. This is because we often do so based on our previous experience; and this limits the ability to think laterally. The important thing, however, is to establish some fundamental principles. Then, having considered how to minimize the risk of failure, proceed. Here, senior management support is vital. When piloting, it is recommended to choose a sector of the business where a good level of commitment already exists. This ensures that if any barrier or problems arise, then they are not just a result of negative attitudes.

Of course there are practical issues to be considered that can limit the continuing development of teams. These will tend to be particular to an organization's culture. However, sustainability is a long-term issue and requires consideration at the level of the individual as much as at the team level. The objective throughout is mobilizing its potential application. This demands investment in the individual in terms of employee development. This is not something on which one can standardize one's approach. Each individual will have particular needs. When those needs are satisfied, each individual will make an important contribution to the team. The Michelin experience is positive, alive, and will help sustain the company as a world leader. Only a small part has been realized, so the future will be full of excitement and promise.

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BIOGRAPHY

Bob Bell entered the textile industry in 1972 after a short career as teacher and head of the english department in a suburban secondary school. His industrial experience began with the Carrington Viyella Group in Northern Ireland in training and as personnel and training manager. In 1976, he moved to England becoming personnel executive of the Warp Knitting Division of Carrington Viyella. In 1980, he joined Michelin Tyre Plc. in the HR function, then as personnel manager, and then in 1986 he became group employee relations manager. Later, the role was enlarged to group personnel manager. In 1993, Bell established Michelin Pioneering Consultancy Group (MPCG) and completed a master's degree. Today, as director of personnel for the Northern Europe region of Michelin's operation and managing consultant for MPCG, he is fully involved in the provision of HR and consultancy services. He is also a director/trustee of the European Forum for Teamwork and chairman of the local branch of the professional institute for promoting good practices in the United Kingdom (Institute of Personnel Development).

CHAPTER 2.11

CASE STUDY: COMPANY TURNAROUND USING INDUSTRIAL ENGINEERING TECHNIQUES

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Oy Devcons Ab
Espoo, Finland

When a company suddenly faces a serious decline in demand resulting in a decrease in sales, the appropriate response is to reduce operating costs as quickly as possible. This means large-scale layoffs and a lean organization. But if the company is to remain a major and profitable manufacturer, it needs to further improve its competitiveness in delivery, performance, quality, and product costs. How can this be done successfully in a small company with a lean organization? This chapter presents an example where effective use of productivity improving industrial engineering practices and techniques enabled a company to recover in a few years from a sudden and massive reduction in sales. The company is now very competitive; sales has reached its previous level and is growing. Profitability has been regained. This case study illustrates the use of various industrial engineering techniques in the complete reorganization of a production unit, resulting in substantial gains in productivity and agility.

BACKGROUND AND SITUATION ANALYSIS

This case originates in a company specializing in the manufacturing and marketing of vault doors, prefabricated strong rooms, ATM safes, high quality security and data safes, and a variety of sheet metal cabinet products. The company, KASO of Helsinki, Finland, is one of the major quality safe manufacturers in Europe and has been in business since 1891. In 1994 sales were about $10 million per year. The company was very profitable until it was hit by the bank crisis in Finland in 1995. Sales dropped by 50 percent and the company was soon in trouble. The workforce was far too large. Of a total of 95 employees, 70 were hourly paid production workers.

The production system, based on cyclical batch production, became inefficient, with poor delivery performance and low productivity especially when small batch and make-to-order production was necessary. The entire factory was in disorder, due to batch production and a large variety of products, which further hampered the working conditions. The structure of the organization was functional, with several departments and supervisors. The factory incentive system had not been updated for 10 years, resulting in a state of inflexibility in production and resistance to changes.

The consulting company, Devcons, was contracted in the beginning of 1995 to conduct a survey. As a first result of this survey, changes were made in the top leadership. The owner (CEO) took over the position of managing director and a new production manager was hired, a woman with experience in organization restructuring in the metal industry. The company then decided to start, together with Devcons, an extensive operations development program aimed at installing a new agile and competitive production system and achieving substantial cost reductions to secure continuation of the company.

The available time frame for the change was about two years, and a reduction of personnel, to match the new market situation, had to be started immediately. Investments had to be low and products could not be altered for improved manufacturability in this short period of time. Results had to be achieved basically through labor productivity improvement. Prior to the survey, the company had also started the installation of a new computerized production planning and control system and a certification process of the ISO 9000 quality system. This meant that scarce industrial engineering and management resources were available for developing the production system, especially after the personnel reduction. Therefore, it was extremely important to use simple but efficient industrial engineering tools and to get the operators to complete much of the development work.

When the development program started in April 1995 the situation was such that the personnel had to be reduced within a few months from 70 to 40 production workers and from 25 to 15 salaried personnel.

These were the starting points for the development program: a company and its personnel in a crisis, a complete reorganization of the production system and significant cost reductions as quickly as possible, quality system certification of the company, installation of a completely new computer system, and small development resources.

OBJECTIVES AND SCOPE

To achieve the necessary cost reductions three main, numerically measurable goals were set:

1. Minimum of 30 percent improvement in labor productivity
2. Minimum of 50 percent reduction of production throughput times
3. Reduction of inventory by at least $200,000

The productivity improvement potential was obtained in the survey by evaluating three productivity factors: (1) *methods,* (2) *utilization,* and (3) *skill/performance.* Based on the situation, a productivity improvement of 30 percent was considered possible to achieve, mainly by improving the labor utilization and to some degree by methods improvement concerning material handling and storage.

To estimate the throughput time potential, current data of certain volume products were compared to what could be achieved in a small batch flow production. The potential reduction of inventory was estimated based mainly on the possibility of radically reduced finished goods inventory and shorter throughput times.

The goals would be achieved by only low-cost changes with the present technology and a large product mix. To achieve the numerical goals and be able to manage the operations in the company with an extremely lean organization, the following development objectives were established:

- A make-to-order process with excellent delivery performance
- A simple but effective production planning and shop floor control system

- Trouble-free manufacturing conditions with efficient labor utilization
- A factory and manufacturing process functioning in excellent order (to support marketing)
- A production system and organization totally based on teamwork (no supervisors)
- Short, visual material flows, efficient work place layouts, and multitasking
- Completely new and reliable time standards, easily usable and with complete coverage
- A new wage system, designed to promote efficient teamwork and productivity

All these development objectives relied on knowledge in different industrial engineering practices and techniques. In this case, together with an effective project management, five main types of industrial engineering techniques were used:

1. Reorganization of the production system into a team-based, make-to-order system including factory layout planning and workplace methods development
2. Installation of a shop floor control system for team production including kanban parts ordering
3. Development of engineered standards for a large number of technologically different products using MaxiMOST® work measurement systems and regression analysis*
4. Design of a wage incentive system for teamwork
5. Improvement of teamwork performance systematically using the productivity factors: methods, utilization, and performance

ORGANIZATION OF THE DEVELOPMENT PROGRAM

The program was divided into five separate phases or subprojects:

1. Planning of the new production system, organization, and plant layout
2. Development of the new wage system
3. Development and installation of safe products manufacturing teams
4. Development and installation of parts manufacturing teams
5. Development and installation of sheet metal products manufacturing teams

The allocated time for the entire program was 2½ years. The planning phase needed three to four months, whereafter development and installation were to be implemented on a team-by-team basis (see Fig. 2.11.1).

The development organization followed a normal consulting program structure consisting of a steering committee, a cooperation council (reference team), a program management team and a varying number of task teams. Several seminars and courses were arranged by the consultants for the employees.

The steering committee, the main decision-making body, was chaired by the CEO. It was made up of the company's management team of three persons and two consultants. A total of 16 steering committee meetings were held. The cooperation council, headed by the production manager, consisted of human resource representatives (seven members) and its role was to discuss development suggestions and changes before final decisions were made in the steering committee. Wage system negotiations were, however, handled separately within the established organization of the company.

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* MaxiMOST® is a registered trademark of H. B. Maynard and Company, Pittsburgh, Pennsylvania.

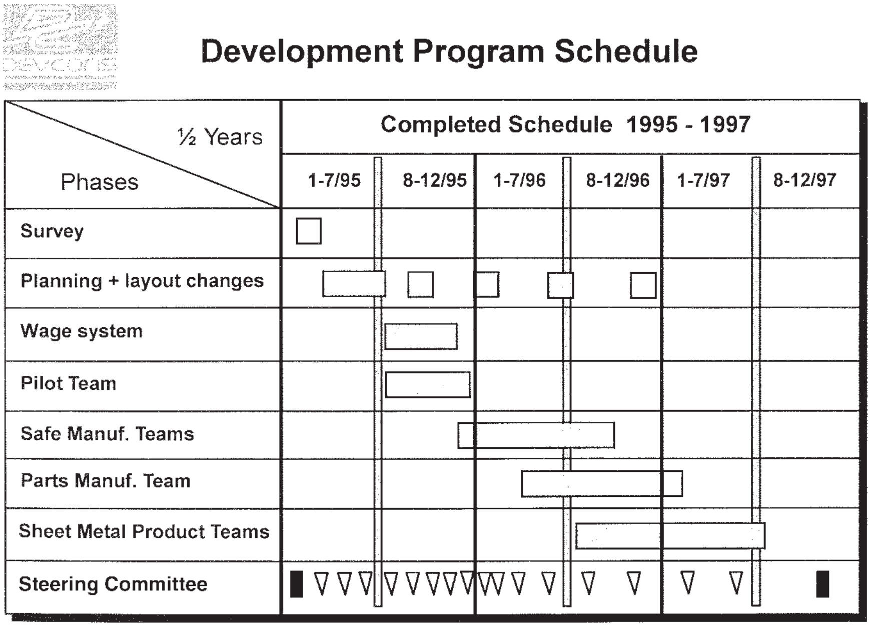

FIGURE 2.11.1 The program schedule.

The program management team consisted of the project manager (the production manager) and two consultants. The task of the program management team was to create the necessary task teams and plan and guide their jobs. The roles of the consultants were divided so that one specialized in the wage and performance reporting systems and the other in the development of team production, methods, and standards.

The task teams consisted of a team leader and members chosen for specific tasks. Task teams were formed in the planning phase for several different tasks, such as process and layout planning, making changes in the wage system, developing the production planning system, improving sales systems, and cleanup of the factory. All production teams and other organizational teams formed task teams in the subsequent development phases.

APPLICATION OF INDUSTRIAL ENGINEERING TOOLS

Reorganization of the Production System

The initial survey indicated clearly that the most effective production system to meet the required objectives was a cellular system based on teamwork. To install this successfully, a four-step process was used:

1. Planning of the process, layouts, and changes, and setting of detailed targets
2. Detailed development of the teams including methods and teamwork development, work contents of team products, and incentive and control systems
3. Carrying out planned changes and installing teams
4. Achieving targets by variance analysis, troubleshooting, and improving teamwork performance

CASE STUDY: COMPANY TURNAROUND USING INDUSTRIAL ENGINEERING TECHNIQUES

The last step will be described later as a separate industrial engineering tool under the heading of improving the teamwork performance.

Step 1—Planning the Process. Planning the new system and making it acceptable to the employees was the primary task in the program planning phase. The planning contained the following procedure:

- Processing production system ideas, obtaining acceptance of them, choosing solutions for teams, and forming a pilot team
- Creating a good and practical plant layout based on low cost changes
- Discussing with the sales team new ways to handle client orders and the division of end products into ABC classes based on delivery times
- Offering courses for key persons in teamwork and the use of the MaxiMOST technique
- Determining productivity improvement potential by making a test analysis of one important product made by the pilot team
- Defining teamwork scopes and responsibilities
- Defining shop floor control principles
- Establishing the preliminary size of teams based on the productivity improvement potential and the present production volume

The planning phase revealed a clear vision of what was required, a commitment from most of the personnel to this vision, and a realistic change plan together with a new plant layout. Necessary plantwide layout changes were started immediately after the planning phase.

The new production system, where all teams formed work and cost centers, was designed based on four product assembly teams, three functional teams, and one support team. The assembly teams were each responsible for their own group of products, thus controlling the output of the factory. Two functional teams (painting and final operations) completed the products from two assembly teams. Another functional team, parts manufacturing, made parts from raw materials for all other teams. A support team handled all previously separate nonmanufacturing activities such as after sales service and repair, prototype manufacturing, and plant and tooling maintenance (see Fig. 2.11.2).

All products produced by the company were divided into three classes based on delivery time: A = 24 hour domestic service (a limited amount of safes in finished goods store), B = 10 days, and C = over 10 days (proposal based). The new product delivery classes meant that parts and components for A and B products had to be buffered in kanban stores just before assembly, while C product parts would be made from scratch. Thus, the manufacturing throughput time of A and B products was assembly time plus painting and finishing times. The minimum throughput time of these products was about 3 to 4 days so that a delivery time of 5 to 10 days, including sales routines (except for C products), could easily be achieved in accordance with the goal. This also made it possible to combine orders in assembly to save setup times.

Step 2—Detailed Development of the Teams. The next step, the development phase, included the design of a new factorywide wage incentive system and detailed development of team methods and standards. The wage system was completed parallel to the pilot team development. The team development procedure involved:

- Planning of the team area layout considering all team products, flows and operations, workstation methods, equipment, and parts handling and storage
- Design of a shop floor control system considering work orders, parts ordering by kanban cards, quality procedures, and productivity measurement
- Definition of methods and work content of a representative sample of products using MaxiMOST

CASE STUDY: COMPANY TURNAROUND USING INDUSTRIAL ENGINEERING TECHNIQUES

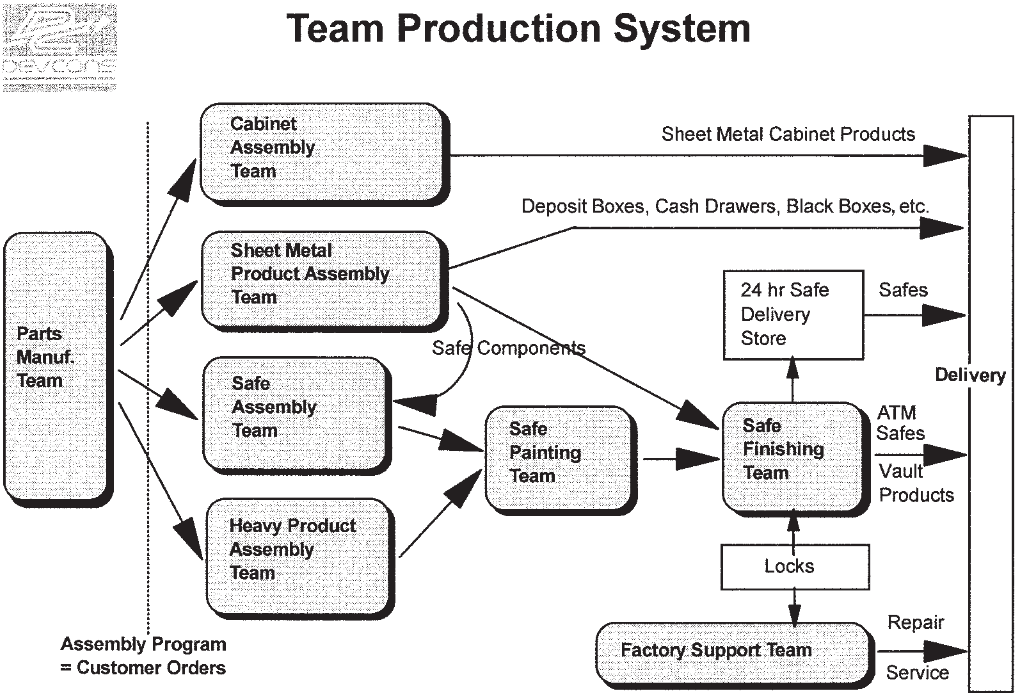
DEVCONS
Team Production System
Parts Manuf. Team
Assembly Program = Customer Orders
Cabinet Assembly Team
Sheet Metal Product Assembly Team
Safe Assembly Team
Heavy Product Assembly Team
Safe Components
Safe Painting Team
Safe Finishing Team
24 hr Safe Delivery Store
Locks
Factory Support Team
Sheet Metal Cabinet Products
Deposit Boxes, Cash Drawers, Black Boxes, etc.
Safes
ATM Safes
Vault Products
Repair
Service
Delivery

FIGURE 2.11.2 Flowchart of the team production system.

- Creation of a simple-to-use standard time system based on the sample of analyzed team products and utilizing regression calculations
- Calculations of all team products using the standard time system, with Excel software

The shop floor control system was initially designed to function partly manually using papers and stand-alone personal computers (PCs) and partly using the old computer system because the new one was not available.

The work content of the first sample products as initially analyzed based on current methods, which were then changed to meet the teamwork requirements (including necessary indirect work), the team area layout, and workstation methods. The rest of the selected products were then analyzed directly based on the new requirements. In many cases workstation layouts were also redesigned according to the analyzed method changes.

Step 3—Implementing Planned Changes and Installing Teams. The third step was divided in two parts, one part concerning overall factory and operation changes and the other part concerning teams. Physical changes and trimming of the organization were already initiated during the planning phase. This step consisted of the following procedure:

- Execution of layout changes, together with a cleanup of the facility, team by team in the order the teams were formed and installed.
- Installation of teams including start-up meetings, introduction of new team labor reporting (actual used hours and finished products) and incentive system, reorganization of workstations and parts storage, and start-up of kanban procedures.
- Trimming of operations and sales routines and elimination of unnecessary jobs.

- Determination of necessary layoffs. No supervisors were needed in the new production system.
- Organization of the remaining office personnel into three teams: sales, production, and operations support (finance, wages, quality, etc.), managed by the CEO, production manager, and the finance manager respectively (see Fig. 2.11.3).
- Change of the production planning and work order system with regard to the new teams, while the operators still functioned on individual incentives.
- Tailoring and installation of the new computer system parallel with the change of the production system.

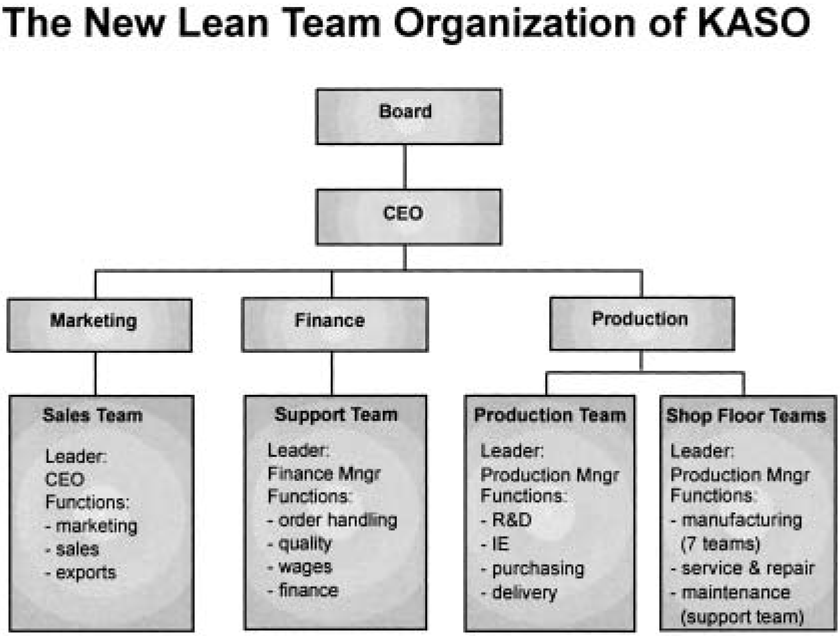
The New Lean Team Organization of KASO
Board
CEO
Marketing
Finance
Production
Sales Team
Leader:
CEO
Functions:
- marketing
- sales
- exports
Support Team
Leader:
Finance Mngr
Functions:
- order handling
- quality
- wages
- finance
Production Team
Leader:
Production Mngr
Functions:
- R&D
- IE
- purchasing
- delivery
Shop Floor Teams
Leader:
Production Mngr
Functions:
- manufacturing
(7 teams)
- service & repair
- maintenance
(support team)

FIGURE 2.11.3 Organization chart.

The most important technical change regarding the new production system was that one team served as just one work center and operation. This caused a long-lasting reengineering of the product structure data.

All parts manufacturing was concentrated to one team for technological reasons (costly fabrication machines), serving the assembly teams as a subcontractor. The assembly teams were divided in two safe teams and two sheet metal products teams. Of the safe teams one made heavy welding ATM safe and vault products, while another team made office safes in a couple of lines all using the same concrete filling station. The making of subassemblies from parts delivered by the parts manufacturing team was incorporated in these teams (in separate workstations). The painting and the final operations (outfitting of locks, drawers, etc., and cleaning and packing) of these products were handled by two separate functional teams because of common facilities and special skill requirements.

The sheet metal products teams included all processes from welding, mechanical assembly, and painting to finishing and packing. One of these teams also acted as a component manufacturer, making sheet metal outfitting products, such as drawers and urethane-molded data safe components for the safe assembly and finishing teams. A special urethane molding line belonged to this team.

The size of these production teams ranged from a maximum of 9 persons (parts manufacturing) to 3 persons (safe painting). The total number of production workers was 40 at the completion of the program, 34 in production teams, and 6 in the support team. Depending on the workload, up to 7 multiskilled operators could be switched between teams.

This new production system dramatically simplified production planning and control. Instead of a series of 15 to 20 controlled operations, only 7 were needed. The four assembly teams formed the capacity planning constraints, governing the entire production process. The work loads for these teams could be planned directly according to sales. The planning of parts manufacturing was also delegated to the teams. The assembly teams ordered parts directly from the parts manufacturing team, mainly using kanban cards. The postassembly teams in turn processed whatever came from the assembly teams. Certain purchased components were also handled by kanban techniques with teams responsible for the replenishment.

Installation of Shop Floor Control and Kanban Techniques

The development of the shop floor control system was a matter of simplifying and delegating routine tasks to the teams. The most important factor was the simple team-based process (one team = one operation) built around product-focused assembly teams. The next important factor was the division of products according to predetermined delivery times (ABC classes) and the introduction of kanban parts ordering. Customer orders could then be directly scheduled to the assembly teams, which simplified the production planning.

Two different ways of work ordering were needed, one for end products in assembly and one for the part and component manufacturing. Teams behind assembly used the same work orders as the assembly teams. The assembly team work orders were simply a once-a-week rolling four-week list of customer orders with scheduled dates of completion and copies of the sales orders. The first week in the list of orders was firm; the following weeks showed the order stock. All teams were allowed to organize their jobs and batching products as best they saw fit, but schedules had to be kept.

Work orders for the part and component manufacturing teams consisted of a part operation card connected to a drawing. Cards were kept in visible racks in the work areas from where the team could plan their production and pick cards to track parts in process. The card could be either a kanban card or a non-kanban card, color coded to show the difference. On these cards all necessary work data was shown, such as structure data, batch, delivery date, bar code, list of suboperations, and standard times. Kanban cards were used only for parts buffered in the assembly or finishing teams (A and B classed products). Non-kanban cards were made by the design engineers when a C class product was ordered.

Kanban cards were kept in racks at the parts storage from where they were brought to the parts delivering teams and returned with the parts. A red copy of the card showed, when left in the rack, that a part replenishment had been ordered. On kanban cards, batch and delivery days (5 to 10 days usually) were preprinted. To determine the delivery date, assembly teams marked on the plastic pocket of the kanban card the date when it had been forwarded to the delivering teams. All kanban parts had their own fixed storage location and could be checked visually. In some cases a two-box storage cabinet was used. An example of a kanban work order is shown in Fig. 2.11.4.

All products were reported by the team using bar coding (incorporated with the new computer system). Any team member could report. In the beginning of the development, when the new computer system was yet to be installed, assembly teams marked completed products and amounts on a paper where all team products and their standard times were prelisted. Parts manufacturing, however, could not report produced parts until the bar coding was in use

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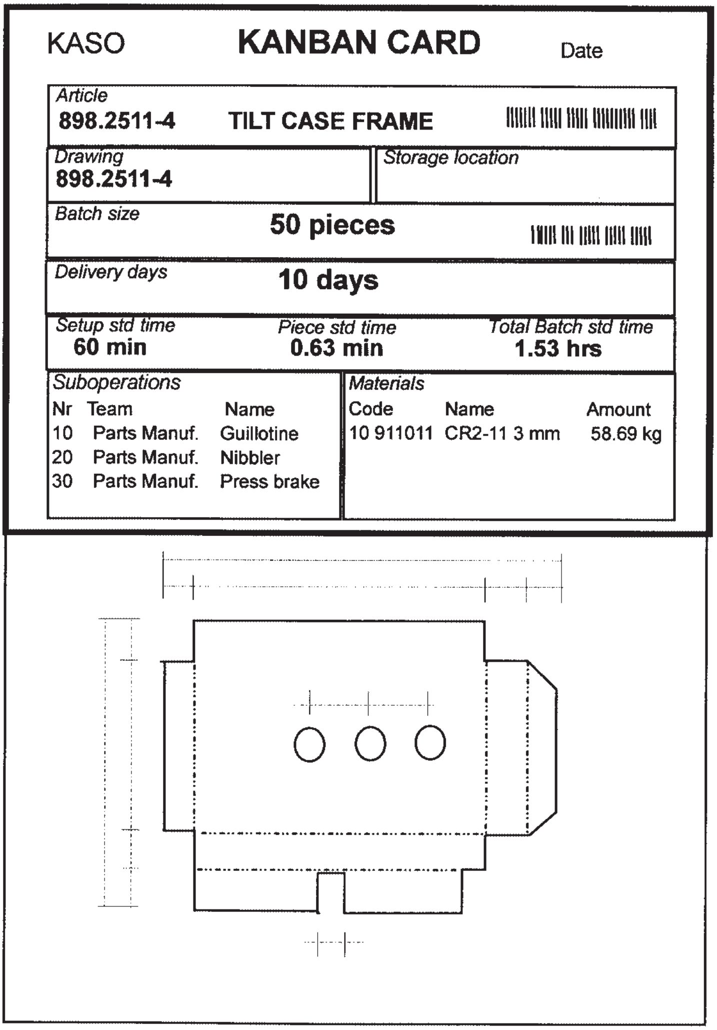


KASO **KANBAN CARD** Date

Article **898.2511-4**	**TILT CASE FRAME**	
Drawing **898.2511-4**	*Storage location*	
Batch size	**50 pieces**	
Delivery days	**10 days**	
Setup std time **60 min**	*Piece std time* **0.63 min**	*Total Batch std time* **1.53 hrs**

Suboperations

Nr	Team	Name
10	Parts Manuf.	Guillotine
20	Parts Manuf.	Nibbler
30	Parts Manuf.	Press brake

Materials

Code	Name	Amount
10 911011	CR2-11 3 mm	58.69 kg

FIGURE 2.11.4 Example of a kanban work order.

because of the large number of items. PC terminals with bar code equipment were installed in a few strategic places in the shop (in cabinets to keep dust out). Reports of produced products could be printed out when needed.

The reporting of hours was completely changed because of teamwork. Instead of having individual time cards, team members marked their hours on a team card visible on a team board (where orders, productivity results, etc., were also kept). If team members had been working in other teams, they reported their hours on the time cards of those teams. At the end of the two-week follow-up period, the team added all hours used by the team and reported this information, together with the list of products produced and standard times, to the production manager who then easily calculated the productivity performance of the team (produced standard hours/used team member hours). A graph highlighting this information was returned to the team. In the future this routine was delegated to the teams, using their workplace computers, but during the development phase it was important for the manager to be in control.

Development of Engineered Standards

The most important factor in achieving high productivity is to have reliable standard times. In this case, where standard times for up to 2000 active parts and 1000 components and a large number of end products had to be developed with very limited resources, two different concepts were used. The first was the use of the MaxiMOST technique to get reliable and easily accepted work content data. The second was the use of regression formulas to develop simple-to-use standard time systems.

MaxiMOST was selected because it was based on predetermined time values and its accuracy was suitable for the small batch type and considerable diversity of work in the production cells. It was also easy to understand and fast to use. The method description level and standard values in MaxiMOST are easily observable by operators (the minimum value is 1 millihour = 3.6 seconds). Therefore, adjusting the work content standards of analyzed products together with team members was not very time-consuming for the industrial engineer. This job was carried out at the computer, with operators present, so the results of the changes could immediately be seen.

This process to get the work standards accepted by the operators is important. They must trust the data and understand that the standard times are realistic, otherwise successful teamwork will not occur.

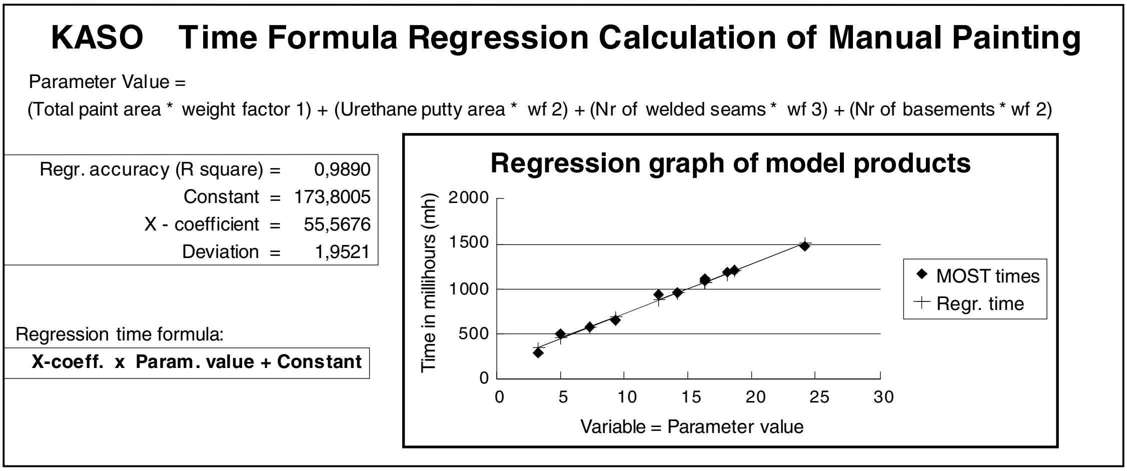
Standard times for single products in single workstations were determined by using direct MaxiMOST analyses. However, in teams and workstations, where many different products and combinations occurred, another technique based on regression calculation was also used. A representative sample of products (7 to 15 so-called model products) was selected and their total work content, measured in labor-hours, including everything that was needed by the team members to produce the product, was then analyzed using MaxiMOST. When possible, suboperations were analyzed separately and used in other model products to calculate the total product work content time.

Then, by using a spreadsheet linear regression calculation as depicted in Fig. 2.11.5, a time formula could be determined by which the standard time of any product or part, produced by the team, could be calculated by inserting a couple of discrete parameter values such as weights, dimensions, part quantities, welds, bends, and holes.

The accuracy requirement for a suitable regression formula was an R^2 value over 0.95. The primary task in creating an acceptable regression formula was to find out the parameters that had the greatest influence on the time it took to produce the product within a team and then to use appropriate weight factors for each parameter to arrive at an acceptable accuracy level. In the parts manufacturing, setup times were separately determined and used (with times ranging from 5.0 minutes to 2.0 hours), but in all other teams, setup times were included in the standard times per unit by using frequency factors.

As a result of this, the standard time calculation could be simplified and included in the design engineering to enhance concurrent engineering practices (see Fig. 2.11.6). By using a spreadsheet, where products and parameter values are specified, the standard time is easily calculated. If the methods of a team change or different products are introduced, the regression calculation can be revised. Then, by changing formula values in the standard time spreadsheet, all values of products listed are updated at once.

An allowance time is by practice not included in the regression formula but added in the spreadsheet. In the KASO case an allowance factor of 25 percent was used generally. This included 55 minutes per day for personal time, 20 minutes for occasional troubleshooting, and about 20 minutes for other non-product-related daily indirect work. Teams must learn to fix



KASO Time Formula Regression Calculation of Manual Painting

Parameter Value =
(Total paint area * weight factor 1) + (Urethane putty area * wf 2) + (Nr of welded seams * wf 3) + (Nr of basements * wf 2)

Regr. accuracy (R square)	=	0,9890
Constant	=	173,8005
X - coefficient	=	55,5676
Deviation	=	1,9521

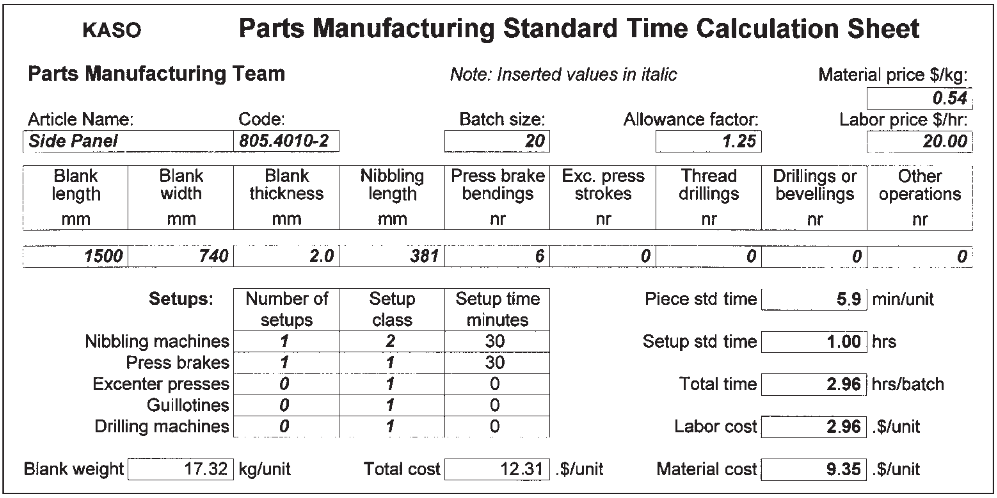
Regression time formula:
X-coeff. x Param. value + Constant

FIGURE 2.11.5 Example of a regression calculation for determining a parameter-based time formula. (*Source: Oy Devcons Ab/Berndt Nyberg.*)

occasional problems by themselves; there are no other resources. In teamwork, one member can use the allowance of other members for problem solving. (The personal time of 55 minutes is selected from a set of predetermined values based on a common agreement between industry unions and employers in Finland.)

The Wage System

The wage system had to be completely changed to create a more motivated workforce interested in teamwork and improving productivity. Wage differentials had been large. Loose



KASO Parts Manufacturing Standard Time Calculation Sheet

Parts Manufacturing Team

Note: Inserted values in italic

Material price $/kg: *0.54*

Article Name: *Side Panel*

Code: *805.4010-2*

Batch size: *20*

Allowance factor: *1.25*

Labor price $/hr: *20.00*

Blank length mm	Blank width mm	Blank thickness mm	Nibbling length mm	Press brake bendings nr	Exc. press strokes nr	Thread drillings nr	Drillings or bevellings nr	Other operations nr
1500	*740*	*2.0*	*381*	*6*	*0*	*0*	*0*	*0*

Setups:	Number of setups	Setup class	Setup time minutes
Nibbling machines	*1*	*2*	30
Press brakes	*1*	*1*	30
Excenter presses	*0*	*1*	0
Guillotines	*0*	*1*	0
Drilling machines	*0*	*1*	0

Piece std time 5.9 min/unit

Setup std time 1.00 hrs

Total time 2.96 hrs/batch

Labor cost 2.96 .$/unit

Blank weight 17.32 kg/unit

Total cost 12.31 .$/unit

Material cost 9.35 .$/unit

FIGURE 2.11.6 Example of regression-based standard time calculation for concurrent engineering use.

incentive rates had raised the pay for some workers, while others had a fairly low fixed wage. Incentive-paid hours were only about 40 percent of all hours. In the new production system, all production teams were expected to work under group performance incentives. The goal was to have incentive-paid hours in the entire plant reaching 85 to 90 percent of all paid hours.

The new wage system consisted of three parts of pay: the first part was fixed based on the job requirements, the second part was also fixed but based on the capability and versatility of the individual, and the third part was a variable bonus based on the productivity performance of the team. The shares of these parts were designed to correspond to 60 percent, 15 percent, and 20 percent of the total target pay. The target pay in the new wage system was determined by stating the company's average earnings per hour to be 5 percent higher than the average value the year before the start of the development program. This new target pay was to be reached at a performance level of 120 percent measured by the new standards.

The variable bonus is a so-called 50 percent bonus, which means that if the productivity changes 10 percent the bonus will change 5 percent. It was important not to use larger bonus shares than this because otherwise labor cost reductions per unit, with labor costs of about $20 per hour, would not occur when productivity is increased. The bonus, in dollars per hour, is the same for everyone in a team and paid in accordance with the hours reported by the team.

The fixed personal part of the pay was determined person by person based on previous pay levels, job requirements for the team, and individual skill levels. In practice this was made by using a spreadsheet containing the pay data of all workers and the calculated total average. Keeping the 5 percent average pay increase meant that in some cases, when skilled workers had raised their pay level due to loose standards, their pay level had to be lowered when low-paid workers were included in the incentive pay. This called for delicate negotiations. Nobody, however, quit because of this. The critical situation in the company and the layoffs had an influence.

Improvement of Teamwork Performance

When a team was established, an initial few weeks of learning teamwork, labor reporting, and quality approval were allocated. During these weeks the productivity level was measured using the new standards. Pay was established to an agreed fixed level. After this fairly short initial period, the incentive pay system started by using a descending learning curve factor to increase earned bonuses. After a couple of predetermined two-week periods, the factor was eliminated. In general it was applied less than two months. The factor could be determined from the results of the initial learning period and varied at the starting point from 1.20 to 1.40.

In the beginning of team implementations, the productivity generally started at a level of 75 percent. For the two assembly teams the level was about 60 percent (one was the pilot team). These low figures caused much concern by the team members, and they of course first said that the standards were wrong. But with a systematic way of first looking at *methods* and then at the *utilization,* the team members quickly learned how to improve the team *performance* to above 100 percent and later up to 120 percent (see Fig. 2.11.7).

Looking at methods meant that a few suboperations were studied by stopwatch (often by the workers themselves). These standards were compared with the corresponding MaxiMOST method descriptions and time values. When methods were the same, the standards by stopwatch and MaxiMOST matched. When the timed method differed from the analyzed one (using more time), either the operator had to learn to use the right methods or the analysis had to be corrected. For the pilot team, quite a few changes were made to the MaxiMOST analyses resulting in an increase of the standards to about 5 percent. However, for the succeeding teams these changes were few. The industrial engineer had learned how to look at methods more carefully to make realistic MaxiMOST analyses. When the team members realized that the standards for the products could be reached, other utilization or skill- and performance-related problems could be addressed.

Examining utilization meant that problems causing extra work (not included in the standards) were to be eliminated. Typical problems included subcontracted foundry components

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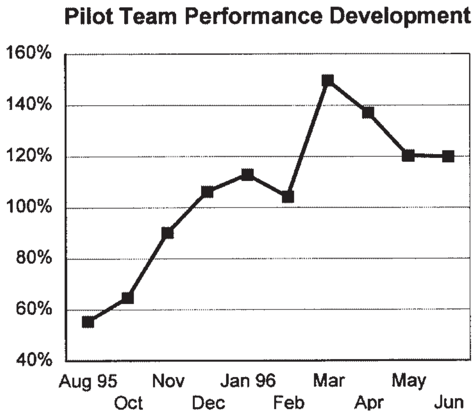


FIGURE 2.11.7 Teamwork installing result.

that were of poor quality causing more grinding or pit filling than was agreed to, or team members that did not appropriately use their kanban cards, thereby causing delays when parts were missing. Skill problems generally did not exist because with the layoffs the most skilled operators were retained. A few personal motivational teamwork-related problems occurred, but within half a year everybody had learned how to be proficient team members.

Problems were discussed in regular team meetings and fixed individually by team members or by special task groups. The measured productivity level was continuously improved and reached the target of 120 percent in teams, where skill and motivation were more appropriate. In two teams, safe painting and parts manufacturing, the productivity peaked at 100 percent. We found that the sizes of these teams were incorrect compared to available load. But with increasing sales, the productivity level has gradually improved with no increase in labor.

IMPLEMENTATION OF CHANGES AND IMPROVEMENTS

Besides planning the development work, the planning phase included the measurement of productivity, organization changes including necessary layoffs, and a transition of the production planning system from make to stock into make to order. Physical changes in the factory, such as layout changes, cleaning up, and making parts and component storages, were also initiated.

The measurement of productivity improvements was accomplished by comparing earned labor-hours for a sample of six representative products at the start of the program and when it was completed. At the start, only data of direct cost standard hours was available. This data was based on over 10-year-old stopwatch time studies and did not include all the indirect work that existed in the present functional production system. The problem, which is quite common in functional systems, was solved in this case by dividing all earned hours from a certain period by all produced direct standard hours. The resulting factor of 1.43 was then used to increase the direct standard hours of the selected sample products. The actual number of hours for these products ranged from 1.6 to 77.4 hours (at the program start).

Productivity improvements could then be reliably determined after the completion of the development program by using the new engineered standards the same way as previously to determine the change of earned hours of the selected products. The factor was now about 1.11 due to a larger coverage of the standards. The new earned hours values were 30 to 40 percent below the previous figures.

During the first phase, the ISO 9000 quality system certification was also achieved. Thus, more resources were available for the development work in the subsequent phases. The installation of the computer system was halted so that it could be redefined according to requirements of the new production system. Considerable customization had to be made to meet the requirements of team production. This seems to be a rule: Production planning and control computer system packages need substantial and costly customization to fit cellular production systems and teamwork.

After the planning phase the following two phases started in parallel: the development of a new wage system and the creation of the first team—the pilot job. The wage system had to be ready when the first team was installed. About three months were allocated to create the pilot team and wage system and two months to reach a team performance level of 110 percent (from a starting level of 60 percent).

Substantial effort was directed toward the development of the pilot team. The goal was to show success in order to minimize the resistance to teamwork organization and changes. The pilot team was carefully selected according to the following criteria: it should be important for the company (commitment!), have an acceptable workload, move into a clean new layout and be staffed according to the expected productivity. The five operators were selected when the team development started and they took extensive part in the development work concerning mainly physical changes, method development, and work content definition (actually no resources were available other than the team members, one industrial engineer, and the consultant as a change agent).

The development of the six other production teams overlapped, but installations were made team by team. Creating these teams, implementing physical layout changes, and reaching the goals took about 1½ years.

The personnel effort in the task teams, including courses and meetings during the development program, has been approximately 4 person-years by workers and 2 person-years by industrial engineering. The consultants used about 85 days in total.

The planning was mainly completed by the consultants in the form of creating ideas and discussing them in task teams, information meetings, and seminars. Informative seminars were organized on team production systems and the MaxiMOST technique.

Getting capable resources to participate in the program development work was always a concern that was dealt with by the steering committee. *Production* was always the priority that sometimes held back progress within the program.

The number of different products, types, and parts (e.g., left and right doors, safe sizes, component variety, etc.) was extensive. Work order and payment routines could not immediately be simplified; the old systems had to be used in parallel with the new team-based routines until all teams were installed. This forced simplifications in the old systems as well, because with the layoffs, resources were extremely slim. Routine jobs such as calculation of standards and printing of kanban cards was to a large extent completed by university students during evenings and weekends.

Getting sales people to accept both a firm delivery classification and a reasonable inventory of A and B products was at first difficult, but it was made easy later when the new versatile production system was completely installed. Sales and profitability both increased due to improved competitiveness.

RESULTS AND FURTHER ACTIONS

The results of using the industrial engineering tools in this case were excellent. The time schedule was kept and all goals were well reached. A brief summary:

- The continuation of the company is secured. The new competitive operations have helped to increase exports in particular.

CASE STUDY: COMPANY TURNAROUND USING INDUSTRIAL ENGINEERING TECHNIQUES

- Sales has reached the same level as before the crisis, supported by a much leaner organization.
- Productivity has improved 50 percent due to an improved utilization, achieved partly by the new production system and partly by including indirect work in the incentive plan.
- Throughput times have been reduced by more than 50 percent, from three to four weeks to five to eight days.
- Finished goods inventory has been reduced by more than 50 percent.
- The new incentive system has a coverage close to 90 percent.
- The factory is in an excellent condition physically and attitudes have changed from production oriented to market and customer oriented.
- The employees use continuous improvement practices.
- The total cost of the program was less than planned—totaling $ 350,000. The break-even time was about eight months.

A few points of vital importance for the results in this case concerning project management:

- The commitment of the company's management to what had to be done was total—this was the most important point.
- All objectives, development work data, work measurement results, and so forth were kept totally open to the employees. Courses and seminars were offered to increase understanding.
- Solutions to plant and workplace layouts, production team grouping, and method changes were kept on a very pragmatic level and a wide acceptance was sought.
- The understanding of work measurement and a successful collaboration in defining the real work content was made possible by use of the MaxiMOST system.
- Performance measurement of production teams based on data results and combined with a group incentive plan were the main instruments to get the employees to learn effective teamwork and to improve results.

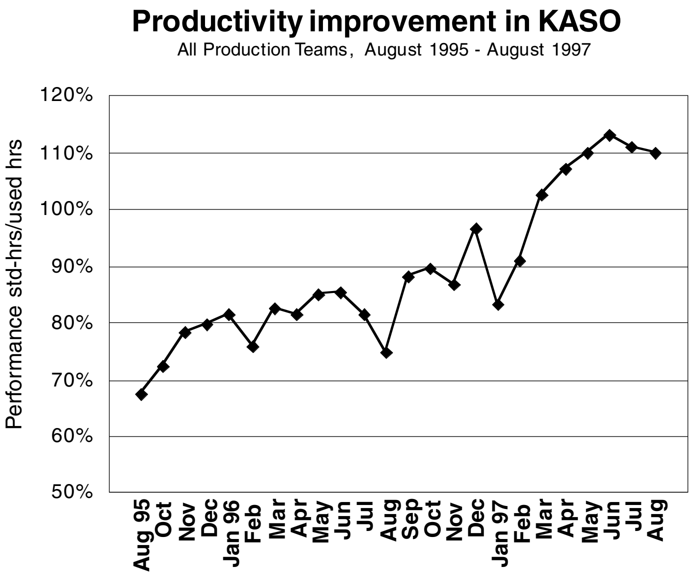


FIGURE 2.11.8 Productivity improvement in KASO.

CASE STUDY: COMPANY TURNAROUND USING INDUSTRIAL ENGINEERING TECHNIQUES

The following evaluation illustrates how the productivity factors were improved:

	Methods		Utilization		Performance		
Before:	0.80	×	0.80	×	1.00	=	0.64
After:	0.90	×	0.95	×	1.12	=	0.96
Increase:		0.96/0.64	=	1.50	i.e. + 50%		
Change:	1.13	×	1.19	×	1.12	=	1.50

This evaluation can be made easier to use for the industrial engineer if "before" values are set to 1000 and productivity changes are compared to this ("after" values = "change" values). The potential of methods can be greater than expected.

The company has now started to redesign and modularize its products to both increase sales and further reduce inventory and manufacturing costs of parts and components. In this project the simple-to-use standard time systems are of great assistance to design engineering.

FURTHER READING

Suzaki, Kiyoshi, *The New Shop Floor Management: Empowering People for Continuous Improvement,* The Free Press, New York, 1993. (book)

Zandin, Kjell B., *MOST Work Measurement Systems: BasicMOST®, MiniMOST®, MaxiMOST®,* Marcel Dekker Inc., New York, 1990. (book)

Goldratt, Eliyahu M., *The Race,* North River Press, Croton-on-Hudson, NY, 1986. (book)

BIOGRAPHY

Berndt Nyberg, born in 1942, has a B.Sc. in naval architecture from the Helsinki Institute of Technology. After a period as a design engineer and production development manager in the metal industry, he joined the consulting company MEC-RASTOR in Helsinki as an industrial engineering consultant in 1974. There he was involved in the development of cellular production systems and the introduction of the MOST work measurement systems in Finland. In 1979 and 1980 he worked for H. B. Maynard and Company in Pittsburgh, Pennsylvania, developing the MaxiMOST system. After returning to Finland he worked for MEC-RASTOR as a consulting manager until he founded, with two other partners, the consulting company Innopro in 1985, specializing in JIT and Constraint Theory Techniques (OPT). In 1992, he joined the management consulting company Devcons, specializing in improving profitability by developing operations of industrial companies. There he has been involved in the reengineering of factories and in the development of highly productive operations and team-based production in Finland and the United States.

Source: MAYNARD'S INDUSTRIAL ENGINEERING HANDBOOK

CHAPTER 2.12

CASE STUDY: IMPROVING RESPONSE TO CUSTOMER DEMAND

Abraham García Ruiz
Norris & Elliott
Mexico City, Mexico

Mexican industry had been protected until recently. When Mexico liberated its trade policy and opened its borders to the world, its businesses were forced to compete internationally with other companies to maintain their markets, as well as to expand to new markets. This was the case of a Mexican company that manufactures zippers for the clothing industry. Because of the commercial change, this company's market share of 85 percent was threatened. It had been able to establish the price, quality, style, and conditions for delivery for its products, but as a result of trade liberation, zippers of similar quality and cost from foreign competitors entered the Mexican market. Their delivery times were much shorter, even though the factories were located abroad. To meet the competition, the first strategy of the Mexican zipper manufacturer was to conduct a project called the Rapid Response Program. This case study presents the project's entire development sequence as well as the results obtained.

BACKGROUND

The Market

For several decades, the Mexican government kept its industries protected, which resulted in a technological backlash and led to the formation of monopolies, since competition was limited to the Mexican market. Manufacturers controlled the major share of the market and established their own preferences, forcing customers to accept what was available at the prices the manufacturers dictated.

Seeking to improve the situation, the Mexican government decided to liberate its international trade and enter the global market, thus creating a free market with international competition and increased technological innovation. Manufacturers therefore started producing products according to the demands in a competitive market, including a high level of quality and service, based on customers' preferences.

Clothing Industry

Because of the arrival of clothing products (including components) from other countries at lower prices, the Mexican clothing industry suffered a major loss of market share. The demand for components manufactured in Mexico for the clothing industry, such as zippers, thread, buttons, and so on, dropped significantly because the market was being supplied by foreign imports. Furthermore, the variety of clothing products as well as the change in trends forced clothing manufacturing companies to maintain component inventories at a minimum to avoid rapid obsolescence.

Component Industry for the Clothing Industry

The clothing component industry absorbed a double blow with trade liberation. First, the demand for components was reduced when a significant amount of clothing was no longer produced in Mexico. Second, the component industry had to start competing with foreign component manufacturing companies that wanted to acquire a share of the Mexican clothing market.

The Mexican CI Zipper Manufacturing Company

Once zippers manufactured by foreign companies entered Mexico through imports or by establishing production facilities in the country, it was observed that price, quality, and variety of the products were very similar. The CI Company was losing market share (from 85 to 60 percent) because delivery times for imported products were much lower than those for zippers made by CI. Therefore, CI general management began to organize a project with the goal of drastically decreasing delivery times to customers and reducing prices and costs, while maintaining quality. The project was called the Rapid Response Program.

To conduct the project and guarantee its success regarding time and cost, and to positively and significantly decrease customer delivery times to a competitive level, CI's management decided to create a multidisciplinary work team composed of managers and employees from all areas and departments involved in attaining the established goals. Rapid Response was designed to address the following key areas of CI's current structure.

Finished Product Warehouse. The finished product warehouse initially employed 40 workers, and contained the necessary facilities and equipment to store large volumes of zipper inventory in 2400 square meters of space. The number of zippers by type, color, and size was very large to supply customers' orders within the shortest possible time, thus maintaining a high level of customer service. This large inventory led to many lost, obsolete, and damaged products—as well as to high costs and expenses in operations and administration because workers needed to manage and control the inventory as well as maintain records about receiving, stocking, storing, selecting, and shipping these products. In cases when a customer requested a zipper that was out of stock, an order for its manufacture had to be placed at a moment's notice, resulting in interruptions, delays, and prolonged response times.

Production Planning. The production planning was accomplished annually, looking at monthly figures and taking into consideration sales of finished products from prior years as well as forecasted volumes. The planning of the components (chain, top, stop, tape, stud, box, and slide) was accomplished from that base, which made it extremely difficult to implement because of the variety of zipper types, slides, colors, lengths, and fashion trends. Three people were needed to perform this activity.

Production Scheduling. Production orders were issued every day for each department including only the operations that were performed in the department. This was done both for the finished products and the components, based on customers' orders received the day before. It also

CASE STUDY: IMPROVING RESPONSE TO CUSTOMER DEMAND

included additional items that the scheduling managers believed were necessary and were therefore added to the production schedule for the current month. In most cases, priorities were established by pressure from those customers whose orders were behind schedule, or by pressure from commercial managers and directors to fulfill commitments to customers they deemed important. Three people were also needed to accomplish this activity.

Production. Production was performed by departments (see Fig. 2.12.1) in which the machines were grouped according to the types of zippers they could produce. CI used the following production departments: gapping, broaching, stoppers, slider, toppers, cut, inspection, and packing.

The process began with the dispatch of the daily production orders from each department supervisor, who then, with the orders in hand, proceeded to visit the component warehouse to select the required components. These components were placed within the department alongside other components from previous production orders, as yet unfinished and undelivered. This created accumulation, loss, and waste of components—as well as loss of time for the operators to search and select. To begin production, the supervisor gave the operators the production orders for execution. If the order being processed was for a large volume, production delays resulted due to the inability to process other orders during the same one or more days. Upon completion of an operation specified on the production order, the operators notified the supervisor, who indicated which order to work on next. The material handler, under the supervisor's directions, then delivered the processed components or products along with the corresponding documents to the supervisor of the next department in the process chain. The supervisor of the receiving department proceeded to count the items and sign a receipt

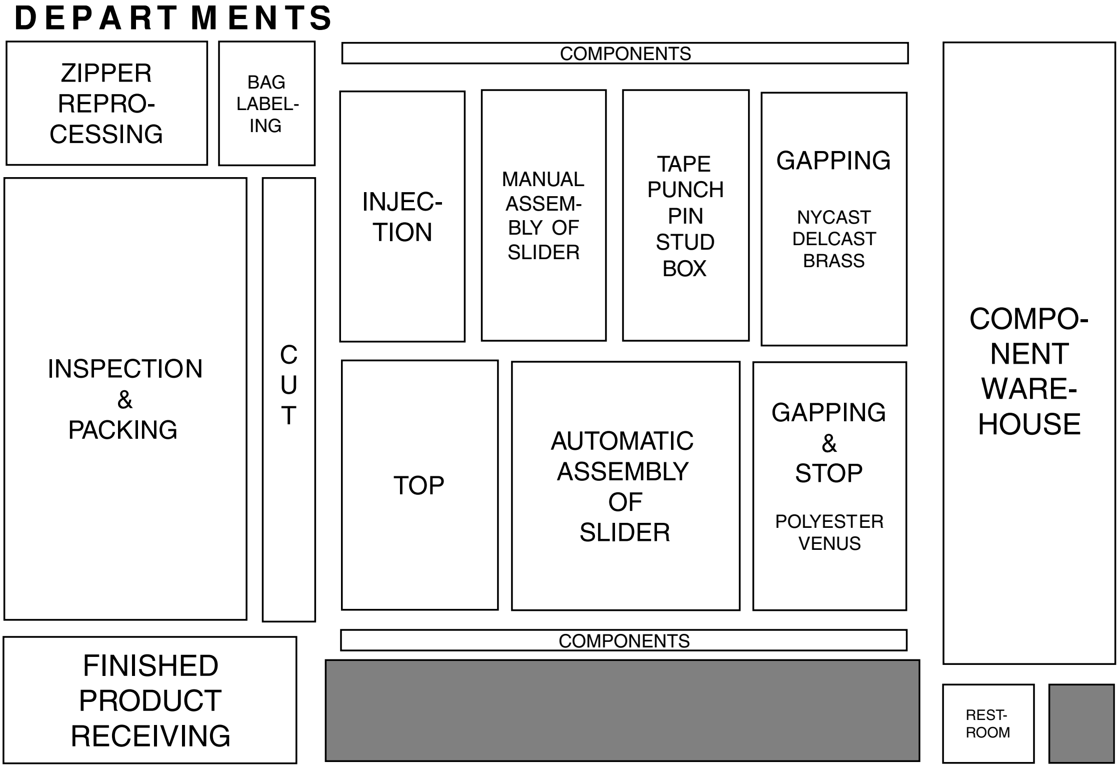

DEPARTMENTS
ZIPPER REPRO-CESSING
BAG LABEL-ING
COMPONENTS
INJEC-TION
MANUAL ASSEM-BLY OF SLIDER
TAPE PUNCH PIN STUD BOX
GAPPING
NYCAST
DELCAST
BRASS
INSPECTION & PACKING
CUT
TOP
AUTOMATIC ASSEMBLY OF SLIDER
GAPPING & STOP
POLYESTER
VENUS
COMPO-NENT WARE-HOUSE
COMPONENTS
FINISHED PRODUCT RECEIVING
REST-ROOM

FIGURE 2.12.1 Layout of the production floor before the Rapid Response Program.

for them. This process was repeated every time the material went from one department to the next. The zipper was being assembled as the process continued. A problem arising with one or more zippers would hold back the progress of an entire order. Production operations required 240 workers and 9 supervisors.

Inspection. All processed items were inspected according to the production order at the end of each operation, and upon completion of the finished products. In case of a defect, all the products in the order had to be reprocessed or thrown away. To perform this activity five supervisors were required.

Material Handling. Material had to be moved from one department to another as production orders were filled. Therefore, it was necessary to have personnel exclusively for this activity, as well as the equipment necessary for the transfer of the processed material (hydraulic lift trucks, forklifts, containers, etc.). Given the large number of ongoing production orders, the material being processed was frequently lost. This meant that a duplicate production order had to be placed, even if the original zipper order would turn up later.

Control and Follow-up. The assembly lead time for products was three days from the beginning of the gapping operation until the product was packed. Because the material passed through six departments, there was neither control nor follow-up during the process. Information about an order was provided only when it was started and then again when it was finished. Only when dealing with one or more specific orders were people assigned to carry out individual control and follow-up.

Incentive Pay. Incentives were paid on an individual basis and by operation, not per finished product, which led to an increase in the cost of labor without completing the product in less time. Also, because of the large number of orders on the floor, workers selected which orders to complete first, choosing the types of zipper that were easiest to process.

Maintenance. Existing maintenance was only of a corrective nature and there was no stock of spare parts to cover at least 80 percent of the most frequent repairs. This contributed negatively to the quality of the products, compliance with the delivery schedule, and rising costs: About 15 percent of production time was lost because of maintenance.

Sorting, Shipping, and Delivery. The sorting and shipping operations were performed during the night shift, after receipt of the day's production. Delivery was made on the following day and thus, whether a zipper was produced as an urgent order, it was delivered on the day after completing the assembly—in the best case. Factors that could cause late deliveries included a heavy workload or unforeseen events that commonly occurred, such as heavy traffic, mechanical failure of vehicles, or absent drivers.

Orders. Orders were taken by the sales agents, usually on the customer's premises, and were kept in the agent's briefcase until the next day when he or she would visit the office. This system turned the sales agent into an order processor, eliminating the opportunity to provide sales or promotional work for the customers and allowing the competition to make advances. Once the orders arrived at the company they were turned over to the credit and collections department for authorization. If an order was rejected, the sales agent had to contact the customer to verify the customer's credit situation.

Credit and Collections. Credit authorizations were being completed manually by examining each of the orders, one by one. Collections were carried out by the sales agent. Accounts were usually updated within three days after a customer had made a payment. On the first day, the sales agent brought the customer's payment in to the office. On the second day, the agent deposited it with the cashier. It was not until the third day that the payment was reported to the credit and collections department, which was in charge of crediting the payment to the account and updating the customer's balance. Occasionally this resulted in a customer's order being rejected although it had already been paid.

OBJECTIVE AND SCOPE

Objectives

From the beginning, the objectives defined for this project were highly ambitious and focused on improving customer service in time, quality, and cost—particularly since the company's position as the market leader was at risk. In addition, the project was to include several departments and a large number of individuals, requiring a considerable financial investment. The project proposed the following objectives and percentage goals:

Decrease in delivery times (from confirmation to delivery of an order)	50	percent
Reduction of work in process	50	percent
Reduction of finished product inventory	30	percent
Recovery of lost market share	10	percent
Reduction of waste and reprocessing	50	percent
Increased control of orders on the shop floor	100	percent
Reduction in operation costs and expenses	10	percent
Reduction of direct and indirect labor	10	percent

As a final objective, the work team hoped to complete the project within 12 months.

Scope

The project would address the following areas:

Component warehouse:	From the reception of components from suppliers until delivery of these same components to production.
Production:	From the moment that the components are received from the warehouse until delivery of the zipper to the finished product warehouse.
Finished product warehouse:	From the time the product is received from production until it is invoiced and shipped.
Delivery:	Delivery of the product to the customer and receipt of payment or documents for later collection.
Production planning:	Planning of the components and products.
Production programming:	Daily programming of the zipper assembly orders.
Production control:	On-floor control of the assembly orders.
Maintenance:	Execution of a preventive and corrective maintenance program—electrical and mechanical—covering the machines and equipment used in the assembly areas.
Orders:	Processing the order.
Credit and collections:	Authorization of orders and deposit of payments.

ORGANIZATION OF PROJECT

Given the magnitude of the project and the short time schedule (12 months), it became necessary to organize development teams (Fig. 2.12.2) consisting of executives, managers, and employees, as well as consultants, to redesign the process.

Each multidisciplinary team was given specific tasks to complete (Fig. 2.12.3) and would therefore not waste time on improvements that did not meet the objectives. Consequently the teams did *not* try to

- Enlarge the warehouse to improve location and assortment of finished products
- Acquire better equipment for the handling of work in process or finished products
- Reduce the process time by adding personnel

The teams would rather try to solve the problems from the root in accordance with the objectives.

PROCEDURE AND APPLICATION OF TOOLS

The procedure employed for the execution of this project is illustrated in Fig. 2.12.4 and is composed of the following phases.

Phase 1—Audit

During this phase, the purpose was to analyze all areas included in the project with regard to total volumes of items in the operations, frequencies of operations, levels of current yields of the processes, the relationship with other processes, labor involved in the execution of the operations, and the infrastructure used.

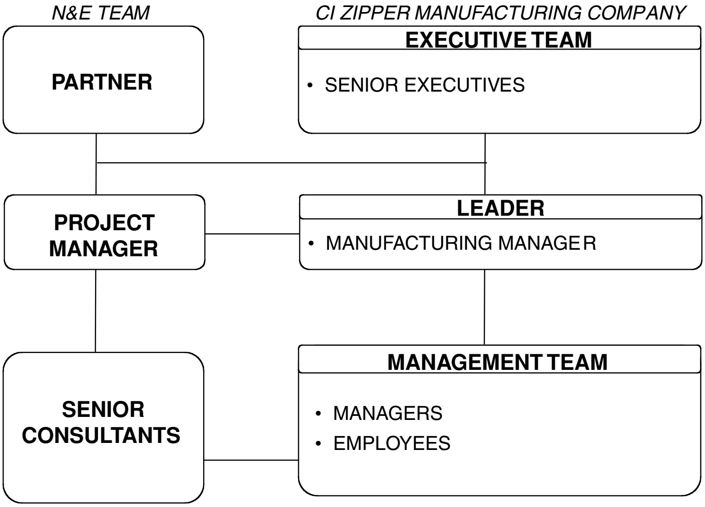
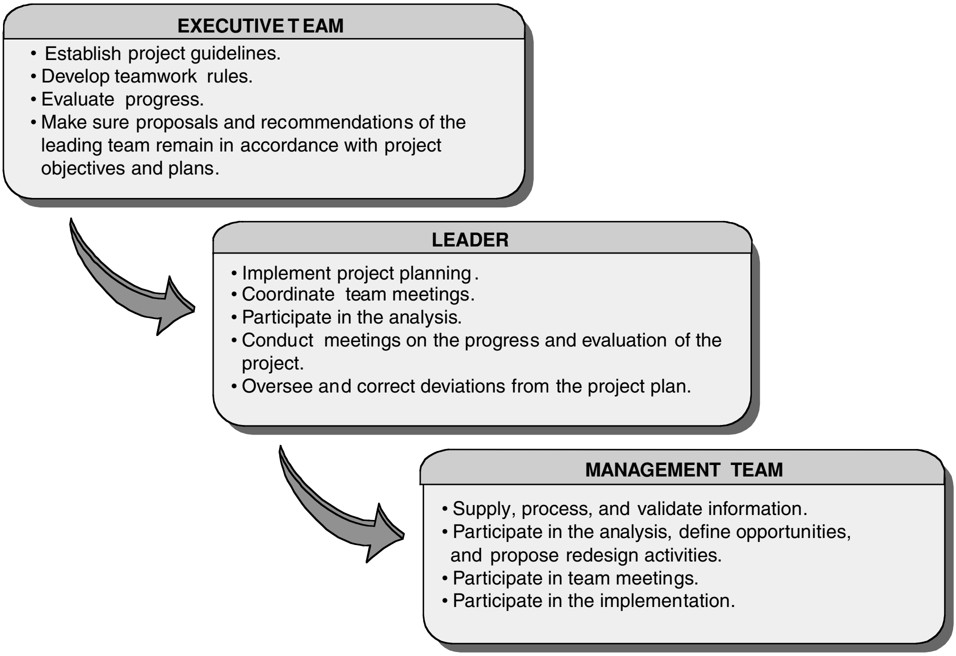

N&E TEAM
CI ZIPPER MANUFACTURING COMPANY
PARTNER
EXECUTIVE TEAM
• SENIOR EXECUTIVES
PROJECT MANAGER
LEADER
• MANUFACTURING MANAGER
SENIOR CONSULTANTS
MANAGEMENT TEAM
• MANAGERS
• EMPLOYEES

FIGURE 2.12.2 Organization of project.



EXECUTIVE TEAM

- Establish project guidelines.
- Develop teamwork rules.
- Evaluate progress.
- Make sure proposals and recommendations of the leading team remain in accordance with project objectives and plans.

LEADER

- Implement project planning.
- Coordinate team meetings.
- Participate in the analysis.
- Conduct meetings on the progress and evaluation of the project.
- Oversee and correct deviations from the project plan.

MANAGEMENT TEAM

- Supply, process, and validate information.
- Participate in the analysis, define opportunities, and propose redesign activities.
- Participate in team meetings.
- Participate in the implementation.

FIGURE 2.12.3 Tasks assigned to participants.

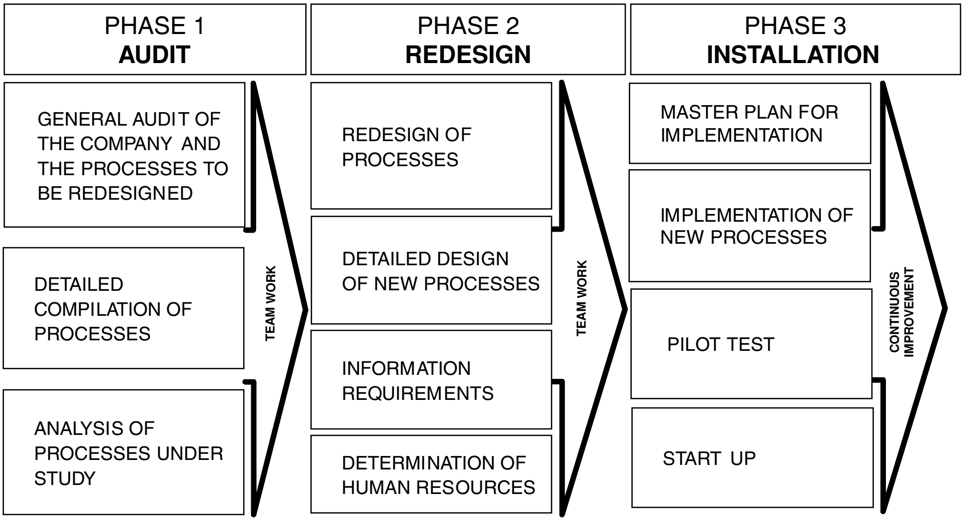

PHASE 1
AUDIT
GENERAL AUDIT OF THE COMPANY AND THE PROCESSES TO BE REDESIGNED
DETAILED COMPILATION OF PROCESSES
ANALYSIS OF PROCESSES UNDER STUDY
TEAM WORK
PHASE 2
REDESIGN
REDESIGN OF PROCESSES
DETAILED DESIGN OF NEW PROCESSES
INFORMATION REQUIREMENTS
DETERMINATION OF HUMAN RESOURCES
TEAM WORK
PHASE 3
INSTALLATION
MASTER PLAN FOR IMPLEMENTATION
IMPLEMENTATION OF NEW PROCESSES
PILOT TEST
START UP
CONTINUOUS IMPROVEMENT

FIGURE 2.12.4 Methodology and plan for implementing a Rapid Response Program.

The work teams asked questions about how the activities were currently accomplished, and subsequently created operational and administrative flowcharts. Further, ways in which the current process measurements, and non-value-added activities, could be improved were identified.

Phase 2—Redesign

Once all information about the activities performed was obtained, the opportunity areas for improvement were identified and solution alternatives were generated through teamwork techniques and process analysis. The alternatives were submitted to the teams to select those that were compatible with the project goals. Concepts and detailed designs of the redesigned process flows were prepared and information requirements demanded by these solutions were established, as were the technical, human, and other resources necessary for implementing the solutions. These included the internal and external customer requirements as well as the company's plans and programs.

Phase 3—Installation

The installation phase started when the developments in phase 1 and 2 were completed. It began with the formulation of a master plan containing implementation strategy, a detailed program schedule containing necessary activities, individuals responsible for performing them, and commitment dates—as well as the definition of human, technical, and other resources necessary for operation of the new processes. When the requirements had been fulfilled, training in the new methods and processes was provided for the employees.

Pilot programs were then conducted in those areas that required them, and subsequently the new processes were released and implemented. These three phases were completed during a period of 12 months, as can be seen in Fig. 2.12.5.

At the end of the audit and redesign phases the causes of long delays in customer deliveries were identified. There were three main causes:

1. Poorly structured production department
2. Lack of a proper system for preventive maintenance
3. Complicated production planning having to consider the type, color, and length of zipper.

Furthermore, problems found in other areas or functions emanated from these problems. The teams then decided to approach these areas or functions first, and thereafter cover the other areas within this new framework, which resulted in the following:

- Changing the production organization from departmental to line-based (see Fig. 2.12.6)
- Developing and implementing a preventive maintenance system
- Performing production planning without considering the length of the zipper

By taking these three major steps, problems with handling and warehousing work in process and finished products, as well as problems with the control of shop-floor orders, were eliminated. The process lead times were significantly reduced, as were many other times, which were affected by these three problems.

IMPLEMENTATION OF CHANGES AND IMPROVEMENTS

Production. The department structure was changed to production lines, based on the type of zipper manufactured. For instance, instead of having all the gapping machines in one

PHASE	No.	ACTIVITY	FEB		MAR		APR		MAY		JUN		JUL		AUG		SEP		OCT		NOV		DEC		JAN	
1	1	GENERAL AUDIT OF THE COMPANY AND THE PROCESSES TO BE REDESIGNED	▨																							
	2	COMPILATION OF THE INFORMATION FROM THE PROCESSES UNDERSTUDY	▨	▨	▨	▨																				
	3	ANALYSIS OF PROCESSES UNDERSTUDY					▨	▨																		
	4	PROBLEM DETECTION AND DEFINITION							▨																	
	5	IDENTIFICATION AND QUANTIFICATION OF INDICATORS OF SUCCESS								▨																
2	6	GENERATION OF ALTERNATIVE SOLUTIONS									▨	▨														
	7	DETAILED DESIGN OF NEW PROCESSES											▨													
	8	DEFINITION OF THE INFORMATION REQUIREMENTS (SOFTWARE, HARDWARE, AND COMMUNICATION)												▨												
	9	DEVELOPMENT, ACQUISITION, AND IMPLEMENTATION OF INFORMATION REQUIREMENTS													▨	▨	▨	▨	▨	▨						
	10	DETERMINATION OF HUMAN RESOURCES													▨	▨										
	11	DETERMINATION OF TRAINING NEEDS															▨									
3	12	MASTERPLAN FOR IMPLEMENTATION																▨	▨							
	13	DETERMINATION AND JUSTIFICATION OF RESOURCES (HUMAN, TECHNICAL, AND MATERIAL)																		▨						
	14	EXECUTION OF NECESSARY TASKS FOR IMPLEMENTATION																			▨	▨	▨	▨	▨	▨
	15	PILOT TEST																					▨	▨		
	16	CONCLUSION OF PILOT TEST																							▨	
	17	FINAL PREPARATION																							▨	
	18	QUANTIFICATION OF BENEFITS																								▨
	19	START UP																								▨

FIGURE 2.12.5 Project schedule.

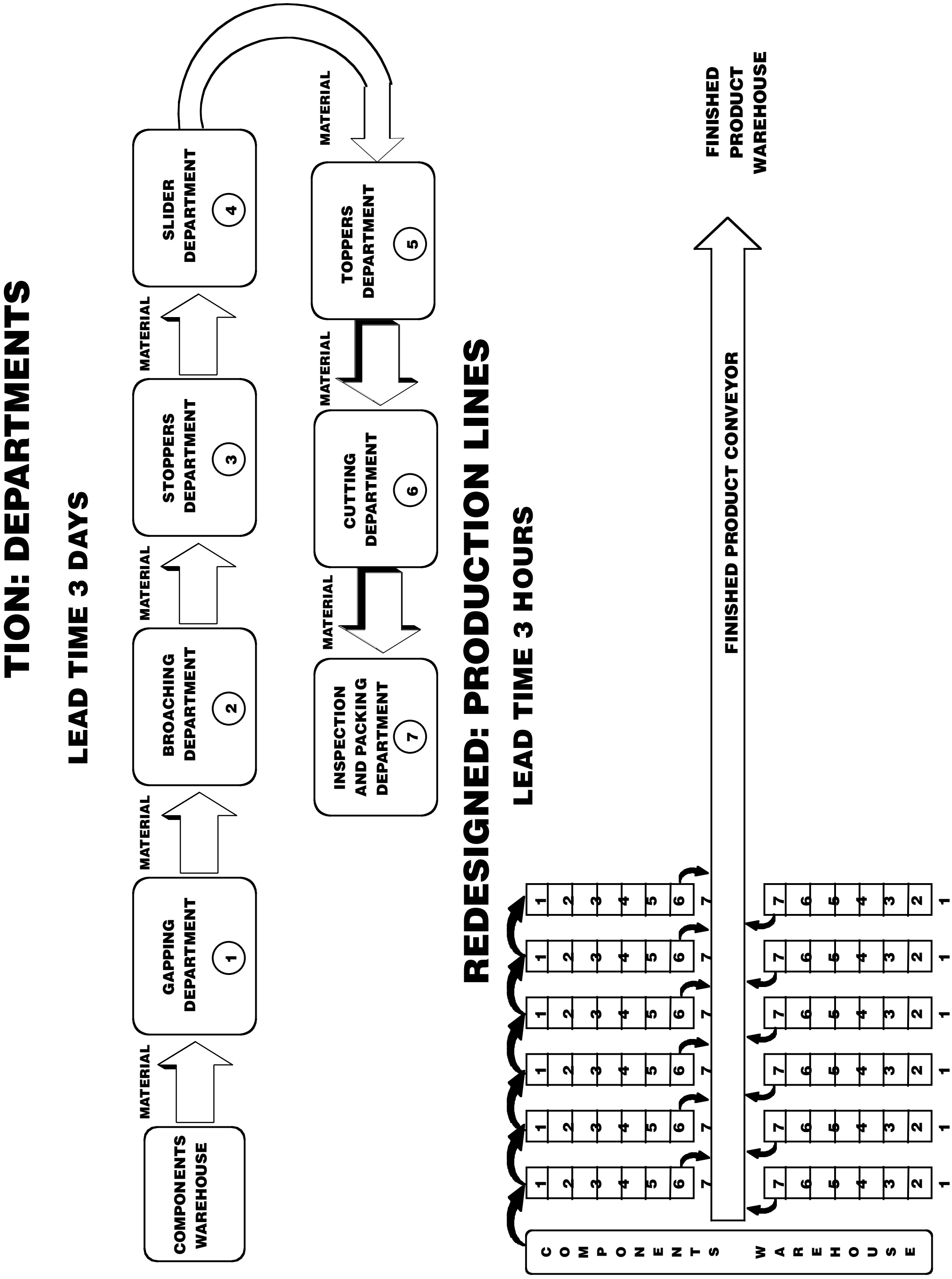

TION: DEPARTMENTS
LEAD TIME 3 DAYS
COMPONENTS WAREHOUSE
MATERIAL
GAPPING DEPARTMENT 1
MATERIAL
BROACHING DEPARTMENT 2
MATERIAL
STOPPERS DEPARTMENT 3
MATERIAL
SLIDER DEPARTMENT 4
MATERIAL
TOPPERS DEPARTMENT 5
MATERIAL
CUTTING DEPARTMENT 6
MATERIAL
INSPECTION AND PACKING DEPARTMENT 7
REDESIGNED: PRODUCTION LINES
LEAD TIME 3 HOURS
COMPONENTS WAREHOUSE
1 2 3 4 5 6 7
FINISHED PRODUCT CONVEYOR
FINISHED PRODUCT WAREHOUSE

FIGURE 2.12.6 Layout of the production floor before and after Rapid Response Program.

department and all the slider assembly machines in another, each production line is now composed of

- 1 gapping machine
- 1 stopper assembly machine
- 1 slider assembly machine
- 1 topper assembly machine
- 1 custom cut machine
- 1 inspection and packing station

The number of production lines was determined based on the sales volume of each type of product (see Fig. 2.12.7):

- 5 lines for the manufacture of the 1000 polyester zipper
- 5 lines for the manufacture of the fixed brass 4 and 5 zipper
- 3 lines for the manufacture of the fixed and detachable Nycast 5 zipper
- 4 lines for the manufacture of the detachable brass 5 zipper
- 4 lines for the manufacture of the fixed and detachable Venus 10 zipper
- 4 lines for the manufacture of 0/20 Venus, 8 Delcast and fixed brass zippers
- 3 lines for the manufacture of 20 Venus, 8 Delcast and detachable brass zippers

The practice of assigning supervisors per department was changed to per group of production lines.

The new process begins when the supervisor of each group of production lines receives the production orders pertaining to the types of zippers that are manufactured on the lines under his or her responsibility. With these orders in hand the supervisor goes to the component warehouse for the components specified on the production orders. The warehouse operators bring these components to the beginning of the corresponding production lines. The operator of the first machine then receives the components to start the first operation. The product is pushed automatically from one operation to the next until all the operations necessary to finish and inspect the zipper have been completed. Packed in bags of 25, 50, or 100, the zippers are then placed on the finished product conveyor, which transports the bag to the finished product warehouse.

This new arrangement *eliminated*

- The handling of materials because the shorter distances between the machines made an automatic and continuous advancement of the items during the process possible, and the finished product conveyor delivered the finished products to the warehouse.
- The necessity of individualized control and follow-up of the operations because orders are finished in less than one day.
- Time spent by production supervisors, or production control persons, in the search and selection of components.
- The need for process control documents between the departments.

The new arrangement substantially *reduced*

- The accumulation, loss, and waste of components.
- The process lead time for finished zippers in the warehouse, because several orders were processed at the same time and continuously.

The necessary direct labor to work on the production lines was estimated at 180 workers and 7 supervisors.

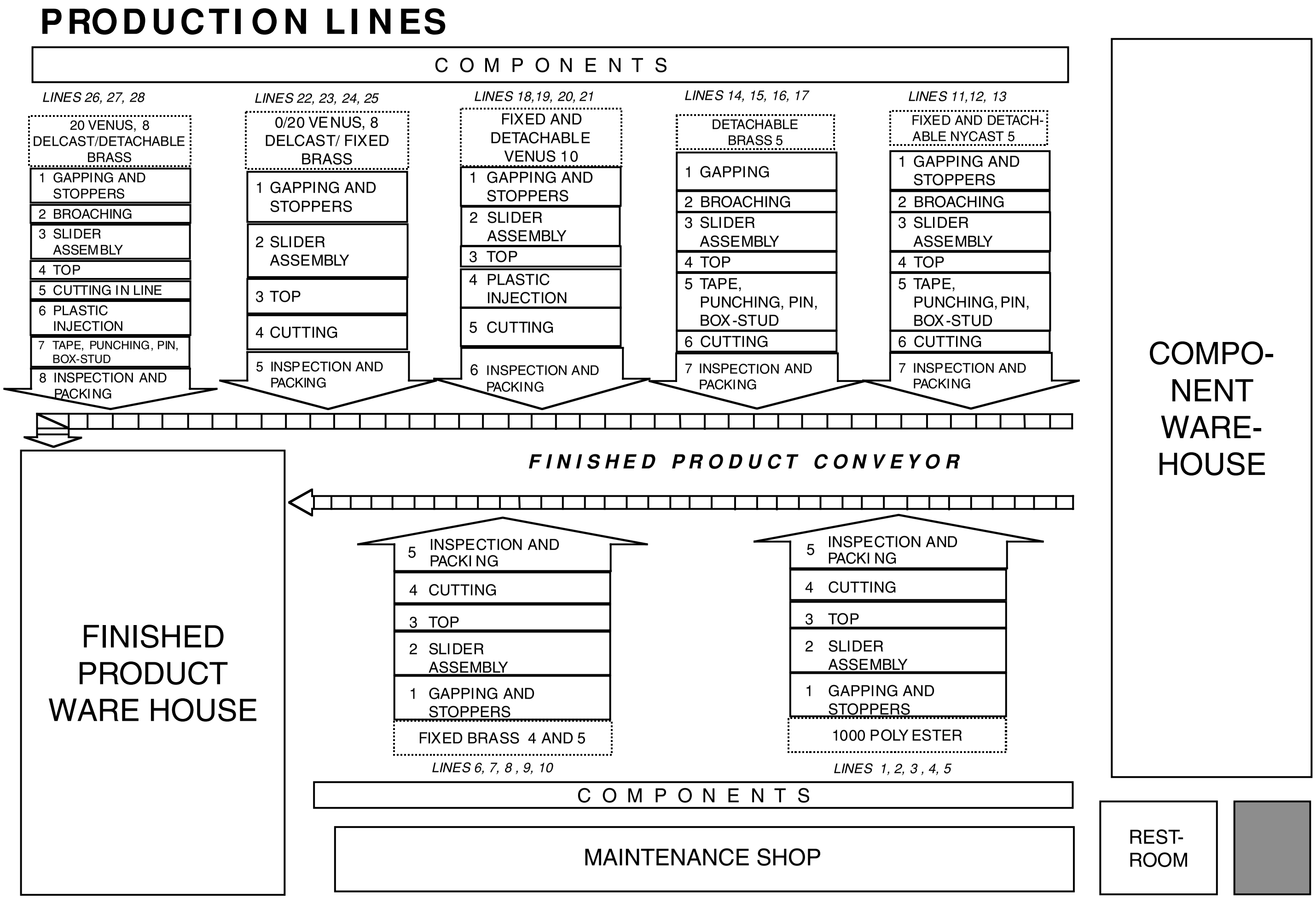

PRODUCTION LINES
COMPONENTS
LINES 26, 27, 28
20 VENUS, 8 DELCAST/DETACHABLE BRASS
1 GAPPING AND STOPPERS
2 BROACHING
3 SLIDER ASSEMBLY
4 TOP
5 CUTTING IN LINE
6 PLASTIC INJECTION
7 TAPE, PUNCHING, PIN, BOX-STUD
8 INSPECTION AND PACKING
LINES 22, 23, 24, 25
0/20 VENUS, 8 DELCAST/ FIXED BRASS
1 GAPPING AND STOPPERS
2 SLIDER ASSEMBLY
3 TOP
4 CUTTING
5 INSPECTION AND PACKING
LINES 18,19, 20, 21
FIXED AND DETACHABLE VENUS 10
1 GAPPING AND STOPPERS
2 SLIDER ASSEMBLY
3 TOP
4 PLASTIC INJECTION
5 CUTTING
6 INSPECTION AND PACKING
LINES 14, 15, 16, 17
DETACHABLE BRASS 5
1 GAPPING
2 BROACHING
3 SLIDER ASSEMBLY
4 TOP
5 TAPE, PUNCHING, PIN, BOX-STUD
6 CUTTING
7 INSPECTION AND PACKING
LINES 11,12, 13
FIXED AND DETACHABLE NYCAST 5
1 GAPPING AND STOPPERS
2 BROACHING
3 SLIDER ASSEMBLY
4 TOP
5 TAPE, PUNCHING, PIN, BOX-STUD
6 CUTTING
7 INSPECTION AND PACKING
COMPONENT WAREHOUSE
FINISHED PRODUCT CONVEYOR
FINISHED PRODUCT WARE HOUSE
5 INSPECTION AND PACKING
4 CUTTING
3 TOP
2 SLIDER ASSEMBLY
1 GAPPING AND STOPPERS
FIXED BRASS 4 AND 5
LINES 6, 7, 8 , 9, 10
5 INSPECTION AND PACKING
4 CUTTING
3 TOP
2 SLIDER ASSEMBLY
1 GAPPING AND STOPPERS
1000 POLY ESTER
LINES 1, 2, 3 , 4, 5
COMPONENTS
MAINTENANCE SHOP
REST-ROOM

FIGURE 2.12.7 Layout of the production floor after Rapid Response Program.

Production Planning. Production planning is still carried out for each year in monthly time periods. However, the sales of finished products from previous years or the forecasts by zipper size are no longer considered. Instead the total number of chain meters consumed becomes the basis for planning. This is a notable change from the procedure prior to this project. Now zippers are not to be considered in the planning as a finished product, based on measurements; instead they are counted by type and color, and the slide with the chain are calculated for total length. Two people are needed for this task.

Maintenance. To attain a 15 percent reduction in nonproductive time of the machines due to maintenance, a preventive maintenance program had to be designed and implemented. That program established the following procedures:

1. List the machines to be inventoried.
2. Code according to cost center, machine functionality, and a running number.
3. Identify equipment to be lubricated and inspected.
4. Identify critical spare parts.
5. Design and implement a format for recording the history of the machines.
6. Make recommendations for the frequency and length of time certain parts should be lubricated and inspected based on the manufacturer's instruction manual and on maintenance, production, and engineering records.
7. List jobs by machine in mechanical and electrical areas.
8. Implement the machine layout.
9. Create a detailed list of mechanical and electrical parts.
10. Develop repair, routine maintenance, and inspection programs.

Based on the conditions of the machines, a rehabilitation program comprising several stages was recommended to bring the machines into optimal operating condition. It was observed that most of the machines had noticeable play in their mechanisms, which was the reason for implementing a continuous and thorough procedure to guarantee that the mechanisms were functioning properly. An optimal inventory of spare parts was established to ensure timely repair of the machines and equipment. The maintenance personnel received training in metrology and measuring practices.

Finished Product Warehouse. The lead time for the production of line zippers decreased from 3 days to 3 hours, and from 15 days to 3 days for special zippers. And, as a result of production orders being available for immediate delivery to the customers, it is no longer necessary to keep a large inventory of zippers in a wide variety of types, colors, or lengths to maintain a high level of customer service. The warehouse operation requires less people (28 instead of 40), and less equipment and space (reduced by 50 percent to 1200 square meters) because the products are manufactured based on actual orders.

Thanks to the new production process the amount of lost, obsolescent, and damaged products—as well as operational, administrative, and financial costs—was reduced.

Production Scheduling. The production of zippers are scheduled each day based on customer orders from the day before, and in the case of urgent orders, from the same day. The orders are given priority on a first in, first out basis, thus eliminating 95 percent of the scheduling manager's decision-making time and pressure from customers and sales managers. Three employees are still required to carry out this activity.

Inspection. Inspection is performed when the first zipper of an order is finished at the end of each production line. Problems are immediately corrected, thus diminishing the possibility of having to reprocess or throw away an entire production order. Three people perform the inspection.

Material Handling. The handling and movement of materials by hand was completely eliminated from the production process because the items advance automatically between the machines. When the product is finished, it is packaged in bags of 25, 50, or 100 zippers, which are then transported by a conveyor to the finished product warehouse. This completely eliminated the use of containers, hydraulic lift trucks, forklifts, and the labor involved in material handling.

Control and Follow-up. Because the zipper assembly lead time was reduced from 3 days to a maximum of 3 hours for most production orders, it is now possible to know when each component in every production order is supplied, at what moment the manufacture begins and concludes, and at what time the products are delivered to the finished product warehouse. Consequently, individualized follow-up and control was eliminated.

Incentive Pay. The incentive system was changed from individual payment per operation to payment of teams for finished products. This eliminated the possibility for operators to choose the simplest products, since orders are processed according to the first in, first out principle.

Picking, Shipping, and Delivery. These operations were reduced by 50 percent during the night shift for two main reasons: (1) an "immediate delivery" system was created featuring same day deliveries to important customers and customers requesting delivery of a large volume of zippers on the day of their orders, and (2) production orders are delivered to the warehouse upon completion. This permits the scheduling of delivery routes on the same day, reducing the process lead time by one day and significantly increasing the number of on-time deliveries.

Orders. Because their function was changed from being order processors to being businesspersons, sales agents no longer take orders. Instead their main function is to call on a customer at appropriate times to promote the sale of products that the customer usually buys and to explore new needs that the customer may have, thereby reducing the threat of foreign competition. Orders are taken by a new customer service department, which is supported by a computerized call programming system that provides general information about the customer. This system also includes updated information on the customer's credit status—in addition to information about the availability of finished products and production order delivery dates, which allows customer service representatives to provide the information that the customer needs. This is a radical change from the concept of waiting for the customer to call; customers are now contacted according to a call schedule, which is updated daily.

Credit and Collections. Credit authorizations for orders were integrated into the system to automatically reprocess orders by customers with overdrawn or overdue accounts. Collections are still being made by the sales agents, who will deposit the money directly with the cashier. Therefore, the account is updated the moment the money is received and the customer's credit status can be obtained in real time avoiding the rejection of orders from customers with paid balances.

RESULTS

The results achieved from this project were quite positive, because the focus was always on improving customer service in relation to time, quality, and cost. The results include the following:

- Reduction in delivery times to customers (from the moment the order is received)
  Line zippers from 3 days to 3 hours
  Special zippers from 15 days to 3 days

- Reduction of work in process from 21 days to 1 day
- Reduction of finished product inventory from 30 days to 7 days
- Recovery of lost market from 60 to 80 percent
- Reduction of waste and reprocessing from 20 to 3 percent
- Increase in control of orders on the shop floor from 20 to 100 percent
- Reduction of manufacturing costs by 20 percent
- Reduction of direct and indirect labor by 10 percent
- Completion of the project in 12 months

CONCLUSION

In any market for any type of product, it is likely that customers would pay a price higher than the price for a competitor's product, provided the quality is superior and the deliveries are reliable and timely.

Many companies, to meet their commitments to customers regarding delivery dates, for example, will increase the levels of their inventory of raw material, work in process, and finished products. This causes problems related to obsolescence, imbalance, waste, and loss, and a need for expanded infrastructure and more space, equipment, and labor for the handling and storage of materials and products. All of this represents higher direct, indirect, and capital costs.

Therefore, we must consider the reduction of the process lead time from order taking to the delivery of the product to the customer as a better option than increasing the quantities of inventory. For flexibility, and the ability to respond as fast as possible to variations in customer demands, the implementation of a Rapid Response Program was of great value for the CI Zipper Manufacturing Company.

BIOGRAPHY

Abraham García Ruíz is a management consultant with Norris & Elliott based in Mexico City, Mexico. His 22 years of professional experience cover 11 years in industry, where he worked as an industrial engineer, plant manager, and technical manager. For the past 11 years he has worked as a consultant and consulting manager, supervising projects in various types of industries. He is a graduate of the National Polytechnic Institute (U.P.I.I.C.S.A.) where he received his degree in industrial engineering.

Source: MAYNARD'S INDUSTRIAL ENGINEERING HANDBOOK

CHAPTER 2.13

CASE STUDY: TRANSFORMING A COMPANY IN CENTRAL EUROPE USING INDUSTRIAL ENGINEERING METHODS

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This case study addresses two fundamental issues: (1) the employment of industrial engineers in countries transforming from the former Soviet bloc and (2) the utilization of industrial engineering methods in a transforming company. The joint venture between the Czech company BARUM and German group Continental AG was selected as an example of both issues.

A brief explanation of the state of the industrial engineering profession in Central Europe is covered in the first part of this case study, as is a discussion of the contributions of industrial engineers in transforming countries. An attempt is made to demonstrate the potential of industrial engineering to solve some of the problems in transforming companies.

The second and main part of the case study covers the utilization of and developments by industrial engineering. BARUM Continental in its present structure is the result of the privatization of a formerly state-owned company. The initial strategy was to integrate it with a leading and strong tire company in a partnership. The partner was to be chosen not only from a financial point of view, but also by its activities and progressiveness in the area of methods and technologies. The case study will discuss how this strategy was implemented in the production of passenger and truck tires through the application of industrial engineering procedures and methods.

The contributions from IE projects such as work measurement, job evaluation, teamwork, total productive maintenance (TPM), quick changes, and process improvements have resulted in excellent business results since the start of the joint venture in 1993.

BACKGROUND AND SITUATION ANALYSIS

At the end of the twentieth century (and into the twenty-first century) the word *productivity* is one of the most frequently encountered words in the countries of Central and Eastern Europe. Productivity is associated with terms such as *standard of living, trade balance deficit, wage level, unemployment, competitive ability, exchange rate,* and other economic terms.

The word *productivity* will be used in two ways. The first is to signify parameters that depict the entire national economy. The second is in reference to a company's productivity level, which therefore reflects the economy of a given region. For the countries of the former Soviet bloc, the struggle for higher productivity has never had greater significance than it does today. Industrial enterprises and corporations providing services are facing increasing competition and a greater need to utilize their resources more effectively. Therefore, high productivity is generally understood to be the factor that will enable enterprises to survive within the European and global markets.

Low levels of productivity or slow increases in productivity have a significant effect on the probability of survival for any economic entity and also considerably deter any increase in the standard of living for the population. There are, however, no direct and straightforward ways to achieve the productivity goals that are necessary in the transforming countries and companies in Central Europe. Productivity is generally considered to be the key toward profitable enterprising and a better standard of living for the entire society. The post-Communist countries cannot really improve their economic situation except by increasing their productivity a great deal. It should be emphasized that they have a lot of catching up to do in this regard.

One country in Central Europe that has started its transition from a totalitarian system toward democracy is the Czech Republic, which is suffering from most of the aforementioned problems. The political situation, which for many years negatively affected business contacts with the surrounding world, changed and opened up the issue of productivity as one of the most important considerations for Czech enterprises and corporations. Rather quickly, the country was confronted with the fact that it could sell products at a profit in economically advanced markets only if the products were produced with higher efficiency and at an acceptable level of quality.

If we compare the productivity levels in the Czech economy with those in advanced industrial countries, we can conclude that the Czech Republic is achieving less than one-tenth of the productivity rate of other European Union countries and the United States. It will not be easy to catch up to the productivity level of the industrialized countries. It is estimated that it will take two or three generations, because the industrialized world is also developing and will not remain stagnant. If the transforming countries, with a long industrial tradition, do not succeed in improving their economies in the near future, they might have to assume the role of exporting raw materials or products with a lower added value. Although this situation has been well known and discussed for a relatively long time, very little is said or written about how to increase productivity. Therefore, very few managers in the Czech Republic at the turn of this century know about the field of industrial engineering, a profession whose mission is associated with increasing productivity. This profession has an enormous potential to increase productivity, and today the transforming countries are beginning to pay much greater attention to industrial engineering than ever before.

In reality, the field of industrial engineering did not exist in cohesive form in the Czech Republic for almost 50 years. Its absence is notable not only in industrial production, but even in the service sector, including health care, financial institutions, public services, and administration. However, historically the former Czechoslovakia belonged to the pioneers who adhered to traditional industrial engineering methods and scientific management. The first president of the newly established Czechoslovakia, T. G. Masaryk, in one of the first government resolutions in 1918, emphasized the need to apply the latest achievements in the field of scientific management from the United States. In the first half of the 1920s, the 1st International Conference on scientific management was held in Prague, and well-known industrial engineering personalities (e.g., Lilian Gilbreth) attended this conference. The shoe company

Bata excellently implemented scientific management methods in order to increase its productivity. Bata, together with other companies, contributed to the fact that Czechoslovakia in the 1930s became one of the most developed and technically advanced European countries.

Industrial engineering has been used in the Czech republic more extensively only since 1989. Even though its core disciplines had been applied in the past, a comprehensive plan for utilizing this engineering field was not implemented. For example, education was not offered at any universities. Besides the traditional work-study methods, rationalized methods based on the so-called Soviet school were used. However, the reality of socialism sometimes distorted even precise methods. As an example, work measurement was affected by ideology. In none of the existing enterprises were there departments of industrial engineering in which individual methods and processes could be developed and integrated. The core activities carried out by industrial engineering were mostly fragmented; an example is the approach to work or salaries within individual departments.

In the 1990s, during the transformation period and with the economy opening up (privatization of state enterprises, joint ventures, direct sales of enterprises to foreign investors), companies were finding that they need to utilize the most up-to-date industrial engineering methods. Departments of industrial engineering have been created in the most important companies and joint ventures (e.g., Škoda-VW, BARUM Continental, ETA, Vítkovické železárny). Industrial engineers, due to shortcomings in the Czech Republic and in the whole of Central Europe, have to rely on the following three main sources for information:

- American sources (e.g., work measurement, teamwork, incentive wage systems, cost control, simulation)
- Japanese sources (e.g., kanban, TPM, SMED, low-cost automatization, production cells)
- German sources (e.g., workplace design, visual management, employee training)

The increased interest by companies in industrial engineering has led to the necessary establishment of industrial engineering programs at universities. In 1994, the Institut průmyslového inženýrství (Institute of Industrial Engineering) was established. The IPI, as it's known, encourages the implementation of industrial engineering methods. It takes advantage of the latest know-how and new methods, which are key to successfully increasing productivity and consequently the standard of living.

The vast majority of enterprises still have to undergo certain changes in order to achieve this goal, which will require overcoming certain negative attitudes in both the macro- and microeconomic areas. If the companies in the transforming countries are to take the measures and commit to increasing productivity, they must go through the following stages:

- To realize that change is necessary
- To acquire knowledge of what needs to be changed and how this change should be carried out
- To be willing to make the change
- To find the balance between the social and business aspects
- To implement the changes by using suitable methods and industrial engineering tools

One firm that has realized the necessity of change and has already made great progress is the traditional Czech producer of tires, BARUM. The company's history is connected with the Bata company, which is known worldwide. Bata started to produce tires for bicycles and passenger cars in the city of Zlín. When the company was nationalized in 1946 after World War II, the annual volume of production reached 600,000 tires. After 1948, the advent of a socialistic regime negatively affected the company's production. The new political system gradually destroyed the tradition, methods, and principles of the Bata's renowned production system. In 1972, a new plant, Rudý říjen (Red October), located near the city of Zlín, was established to specialize in the production of tires. In 1990, the company was transformed to the state-owned joint-stock company BARUM, which produced 2 million passenger car tires that year. During the same year, negotiations concerning the establishment of a joint venture with the German group Continental AG in Hannover started, and in 1993, BARUM Continental, Inc., was founded.

The joint venture with the tire giant Continental AG, the second largest tire producer in Europe and the fourth largest in the world, resulted in the integration of BARUM's tire production with a leading partner. This venture allowed for the investment of capital and the implementation of the most up-to-date technologies and methods. Thanks to the injection of over DM 100 million, (U.S.$60 million) the Otrokovice tire plant is utilizing modern production methods. A restructuring of the production and marketing networks has led to a significant increase in production, productivity, and product variety, as well as an improvement in the quality of tires. The result of this transformation has been that production has quadrupled compared to the early 1990s. The products have been able to compete in the most demanding global markets.

Proof of the quality production at BARUM Continental is the fact that in 1994 the company obtained from the Lloyd's Register Quality Assurance a Certificate of Quality for achieving ISO 9001 standard. In 1997, the company was awarded a certificate for meeting the ecological standards ISO 14001 and EMAS, the first such award outside of the European Union.

Excellent commercial results have been achieved not only due to the implementation of up-to-date technologies, but also due to the substantially higher productivity in the entire production system. This increase in production and quality has been achieved with the same number of employees (3700), who work in four shifts seven days a week in order to make full use of the production capacity and to satisfy demand. With the production of 6.3 million radial tires (70 percent for export) in 1997, BARUM Continental became one of the largest European tire producers. The company's turnover in 1996 amounted to 8.4 billion Czech crowns (U.S.$300 million).

The BARUM Continental plant is turning into a modern production facility comparable to the best in the world. The Continental group is expecting that its plant in Otrokovice will in the future become one of the largest and the most up-to-date European tire production facilities. Its products will be capable of competing with those made in the Far East. Figure 2.13.1 shows the development in the production of tires for passengers cars at BARUM Continental.

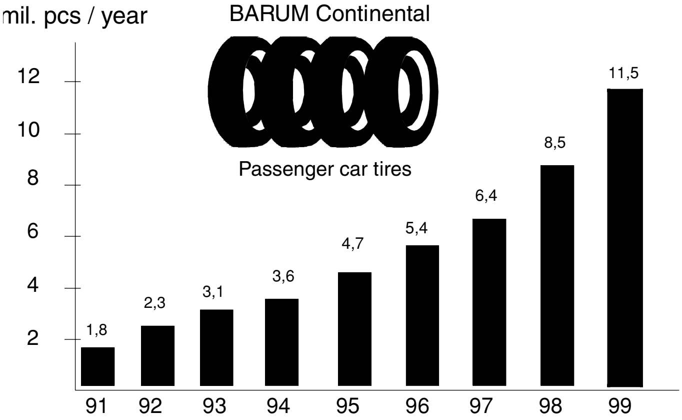

FIGURE 2.13.1 Production volumes for passenger car tires at BARUM Continental.

OBJECTIVES AND SCOPE

The road to the market position achieved by BARUM Continental has not been easy. The entry of foreign capital demanded quick results and a rapid return on investment. Benchmarking studies carried out before the joint venture showed low quality and productivity, insufficient organization of the production process, and low focus by the management on basic production operations. As a result, the effects of socialism were significant, including the lack of responsibility and work ethics. In such an environment, the company's top management decided to carry out the following two projects:

- Establish and develop an industrial engineering department.
- Implement a company program called MORAVA to focus on a continuous improvement of processes and application of the most up-to-date industrial engineering methods.

The objectives were to increase productivity, to implement new methods, to achieve a productivity level comparable to the best plants, and to reduce production costs without additional investments. The objective of the department of industrial engineering, consisting of approximately 20 employees, was first to concentrate on basic industrial engineering disciplines in one selected area and to introduce work study methods not yet utilized, including the following:

- Work measurement
- Capacity reports
- Job evaluation
- Wage system
- Monitoring of productivity
- Benchmarking of processes

The principal objective of the MORAVA program was to implement modern industrial engineering methods, without which the company would not be able to survive into the twenty-first century:

- Continuous improvement of processes
- Teamwork
- Total productive maintenance (TPM)
- JIT techniques (quick-change, kanban, poka-yoke, jidoka, etc.)
- Visual management and control

The name of the MORAVA program was not chosen by chance. It is named after a region in the Czech Republic where BARUM Continental is located and where the principles of Bata's production system (which became famous due to its unique combination of enterpreneurial and social ideas) are still active. People's desire to work, their industriousness and creativity, and identification of employees with the company's goals of high quality and desire to eliminate waste were associated with the Bata company, characteristics that are still remembered by the older generation. The objective of the MORAVA program was to incorporate these ideals into the business environment at the end of the twentieth century so that BARUM would achieve the same level of success as did its predecessor.

ORGANIZATION OF PROJECT

Management realized that the MORAVA program could be an effective tool in achieving the company's business targets. It reckoned that the company's processes showed weaknesses and that therefore industrial engineering should pay attention to the productivity issues and to the sustainable and gradual improvement of the processes. At the same time, it was acknowledged that outside help would be needed. Therefore, BARUM Continental started to cooperate with the Institute of Industrial Engineering (IPI), which participated in the preparation of a methodology and also took part in the implementation of new methods in the production processes and employee training. After a few introductory workshops, the content of the MORAVA program was specified more precisely, especially focusing on the following three basic areas:

- Teamwork in the production process
- Dynamic improvement of processes and waste elimination
- Total productive maintenance (TPM)

The project coordinators were appointed from the managing directors of the production divisions, who, together with other employees and external consultants, were in charge of managing MORAVA. This team monitored the program and directed its development by holding regular workshops.

The following tools were used to introduce and implement the industrial engineering methods that were used to reach the program's objectives:

- Training of the techniques for process improvement
- Workshops focusing on the improvement of processes and elimination of waste
- Interactive seminars concerned with world-class methods
- Management models carried out in the workplaces
- Individual audits
- Visual aids (boards, photographs, charts, one-point lessons)
- Building of communication centers
- Team meetings, company conferences, and so forth

In the beginning, video training programs were prepared in order to increase the transfer of information to employees in various shops. These films (titled *Dynamic Improvement of Processes, Autonomous Production Teams, TPM Maintenance for the 3rd Millennium, First Step in Autonomous Maintenance, Quick Changes*) were accompanied by videos aimed at individual JIT techniques.

PROCEDURE AND APPLICATION OF TOOLS

MORAVA has primarily focused on the establishment of three main pillars through which BARUM Continental plans to reach world-class levels in all its production facilities at the beginning of the twenty-first century. These three pillars are illustrated in Fig. 2.13.2. To achieve this goal, a comprehensive schedule was prepared at the beginning of the program. During the course of the program, industrial engineering methods were added (as illustrated in Fig. 2.13.3).

The program included four phases:

1. Information phase (introduction, pilot workshops related to production, a brief concept of the program)
2. Analysis phase (introductory workshop with the management, establishing concepts for individual areas, public relations)
3. Preparation phase (preparation of individual mediators, selection of topics for workshops, training seminars in world-class methods, team organization, management models)
4. Implementation phase (workshops on the elimination of waste and cost reduction, setting up teams, introduction of TPM, auditing, meetings of management teams)

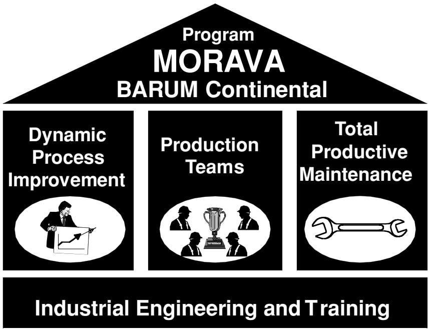
Program
MORAVA
BARUM Continental
Dynamic Process Improvement
Production Teams
Total Productive Maintenance
Industrial Engineering and Training

FIGURE 2.13.2 The pillars of the MORAVA program.

IMPLEMENTATION OF CHANGES AND IMPROVEMENTS

The following part of the case study will focus on the implementation of industrial engineering methods in three basic areas of MORAVA. Permanent improvement of processes has become one of the basic principles of the program. The improvement of production processes in socialistic enterprises has a different orientation than in capitalistic societies, where the main goal is to influence the primary economic indicators (price, cost, profit). In traditional socialistic economies, the prices were fixed, which greatly affected the entire improvement process. After changes in the business environment during the 1990s, it became necessary to

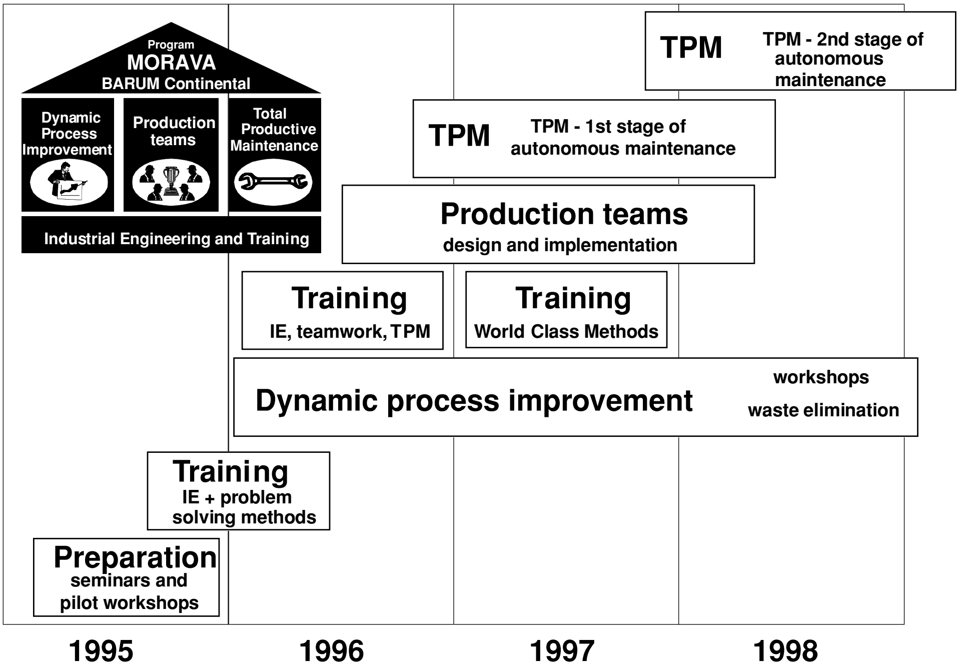
Program
MORAVA
BARUM Continental
Dynamic Process Improvement
Production teams
Total Productive Maintenance
Industrial Engineering and Training
TPM
TPM - 2nd stage of autonomous maintenance
TPM
TPM - 1st stage of autonomous maintenance
Production teams
design and implementation
Training
IE, teamwork, TPM
Training
World Class Methods
Dynamic process improvement
workshops
waste elimination
Training
IE + problem solving methods
Preparation
seminars and pilot workshops
1995
1996
1997
1998

FIGURE 2.13.3 Program schedule.

completely change the methods that led to permanent improvements, because the previous methods did not ensure full utilization of the company's employees.

To make the improvement of production processes more dynamic, BARUM Continental found that the use of mediators contributed to the elimination of waste in any given area. These mediators currently supervise the team's waste elimination activities. The mediator is not a team leader but a catalyst that drives everything forward. He or she is trained especially in the use of interactive moderating methods that make the team more effective by allowing a more active discussion among the participants. The advantage of this method is that everyone can contribute, because it is based on discussions and visual presentation. During the interaction, a large number of shop workers can actively participate in the decision-making and problem-solving processes, which leads to better problem solving.

BARUM Continental uses the workshop as a tool for dynamic development of the production processes. During this workshop, the management and a team of selected workers conduct an in-depth analysis of the production process. This team then forms a special qualified team that resolves problems in a given area. There are eight to ten workers on a team who monitor waste elimination in any area (operators of machinery, technician, foreperson, industrial engineer, shop-floor manager, and service manager). Such workshops were designed to solve problems quickly rather than allowing them to become time-consuming major problems.

The methodology of a workshop was aimed at those areas of waste that could be eliminated in the shortest time possible and, more important, with no or very little financial investment. It was concerned with the unequivocal task performed by modern industry engineering: increasing productivity by invisible investments, especially in the area of work organization.

Workshops were always concluded with the development of a list of measures. The teams gave presentations that were forwarded to the company's management. The implementation of individual proposals was monitored by the team and the management even after the workshops were finished (usually through the manager and division directors, who followed up on specific problems).

The program concerned with the dynamic improvement processes began with the training of mediators. The content of the courses, designed for 60 employees, provided information about current approaches to the improvement of processes, methodology, and to how the workshop was going to be conducted. It also included a hands-on experience in industrial mediating techniques and simple analytical tools used in industrial engineering, as well as providing information about the psychological aspects of teamwork and the resolution of conflicts. The program of dynamic improvement started by training the mediators and by holding pilot workshops. Only after these activities was it possible to launch an avalanche of workshops aimed at current problems and weaknesses in the BARUM production system.

The management of the entire program was quite important, and therefore a program manager was appointed whose task was to coordinate the dates and topics of workshops, to keep records, and to perform other administrative tasks. Regarding quality management, it was important to devote time to repeated and consistent controls, to finding out how the proposed measures were being adhered to, and to supporting their implementation whenever necessary.

Here are some examples of typical results of workshops carried out according to the methodology of dynamic improvement of processes:

- Increased cutter capacity by 100 minutes per day
- Cut the time for replacement of a mold from 240 to 40 minutes
- Increased productivity related to the preparation of mixtures by 15 percent without further investment
- Implemented the circle for kanban and increased continuous production
- Increased the autonomy of the workplace using the concept of jidoka

Productivity gains achieved through the dynamic improvement of processes are illustrated in Fig. 2.13.4, which shows the monthly increase that occurred through noninvestment mea-

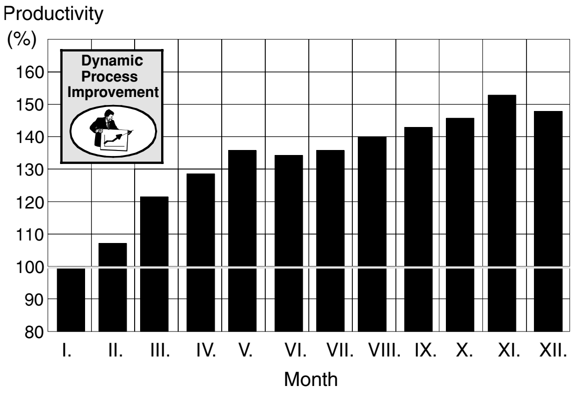

FIGURE 2.13.4 Productivity increase in the production of truck tires.

sures. Because of its advantages, teamwork was introduced as a standard method of organizing production processes.

A *production team* is an organizational unit of workers working together under normal conditions on daytime production that is responsible for the implementation, planning, managing, and improvement of a process or a segment and whose output is a product or service destined for an internal or external customer. Production teams are put in place for an indefinite period of time.

These were not just temporary, elite teams, but were multifunctional teams composed of workers on barrier-free production lines in production cells or units. A system for solving problems by the production teams has been based on the IPI method. Six basic steps had to be taken during the introduction of production teams in order to develop these teams further:

- Creating suitable conditions for teamwork
- Utilizing resources needed for teamwork
- Organizing teams
- Preparing workers for teamwork
- Implementing teams
- Auditing teams

The relationships prevailing between the social and technical systems were used for the organization of teamwork in the production shops. The idea behind this was to make the work more attractive. To facilitate this, the establishment of teamwork included job evaluation, job rotation, job enlargement, job enrichment, ergonomics, a motivating pay system, and multiskill development.

The purpose of applying these motivators in the design of teamwork was to create a multidimensional environment and conditions that would ensure the effective interaction between team members. Because of the multifaceted work of multiskilled workers, the proportion of value added has increased. Combining activities and giving greater authority and responsibilities to the production teams eliminated a significant amount of unproductive work.

The organization of the teams was a specific and demanding task that required experience and knowledge in the field of industrial engineering, because this is the only field that covers the wide spectrum of specialties connected to the design of work systems. It was necessary to consider several factors when the teams were organized:

- The main principles of teamwork
- The organization of workplaces
- The organization of material flow
- The possibility to integrate additional activities into the teamwork or to combine tasks
- Coordination of a team (the role of the spokesperson)
- Determination of the number of the members
- Application of principles of visual management
- Determination of the team's productivity

Internal and external specialists in teamwork, production team spokespersons, and management personnel were used to establish teams and put teamwork into practice. Only after the pilot teams were set up and the first experiences of teamwork in one production area were gathered was the teamwork implemented in all areas of production. At the same time that the teamwork concept was developed, a new pay system was introduced. The department of industrial engineering participated significantly in the creation of the new system. It continued to work on the previously started projects, and it thoroughly carried out job evaluations and extensive work measurement.

The results achieved by the majority of the production teams reflect the advantages of teamwork. Even though the average wage increased, increased productivity caused a decrease in labor costs for each tire produced. In the production operation area, the use of industrial engineering methods gradually increased, although the indirect activities that existed at the beginning of the company's transformation period remained untouched. Significant indirect activities such as repair, adjustment, and replacement of tools, together with maintenance of equipment and handling facilities, were and still remain sources for cost reductions. To achieve this goal, managers and employees had to accept methods that have been used for several decades with great success in the industrialized countries. Among the most important methods were the following:

- Program for making quick changes
- Program of total productive maintenance (TPM)

An obstacle encountered in the attempt to reduce the time needed for the replacement and adjustment of tools was the conservative work habits used by groups of employees involved in tailor-made production. On the other hand, a number of creative solutions helped the managers implement quick changes in the production system. Shop-floor workers were surprised to learn that the methodology of quick change applied in advanced economies could achieve similarly significant results at BARUM Continental (see Fig. 2.13.5). This success was due to the company's program aimed at quick changes. The program emphasized the fact that changes themselves do not add any value to the product and therefore must be considered waste. Since waste is something that should be eliminated, new ways of reducing the time needed for making changeovers had to be included in the program.

It was not possible to achieve a considerable reduction by the use of a single one-time effort performed by one or several workers. Therefore, the program was based on teamwork and the principles of dynamic improvement of processes, including industrial supervision by management. The team structure was based on the concept that the person who performs the work knows best what prevents him or her from making improvements. Therefore, workers who were actually involved in the changeovers attended the workshop and participated in related activities.

It was necessary to achieve changeover time reduction step by step, and seven steps formed the core of the program aimed at quick changes:

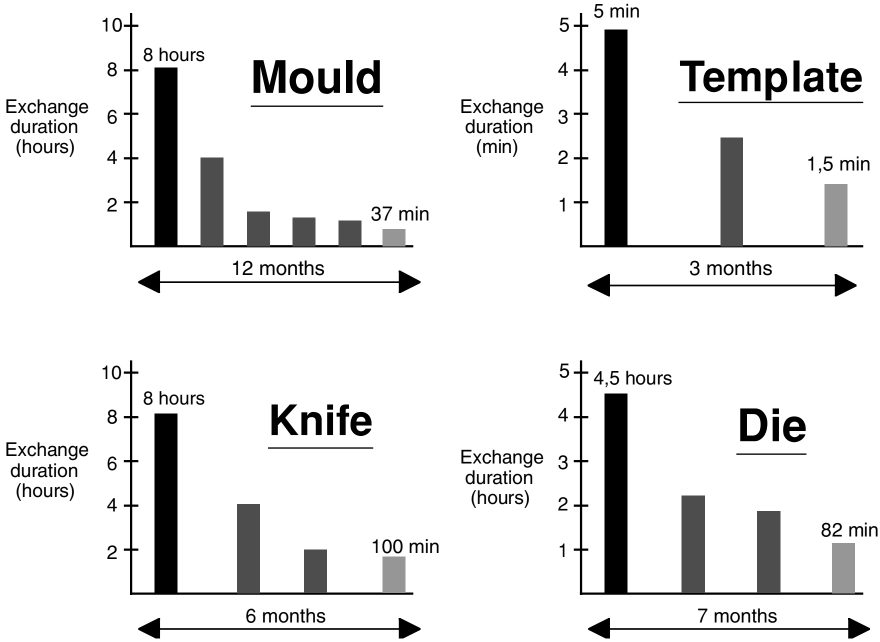

FIGURE 2.13.5 Examples of time reduction in the replacement of tools.

1. Announcement of the program for a specified type of change (goals)
2. Information seminar dealing with the problems associated with quick changes
3. The introductory workshop
4. Training in and practicing replacement (according to the proposed method accepted at the workshop)
5. Implementation of technical measures that came out of the workshop
6. Improvements in the changeover process
7. Evaluation of the achieved results and of the program itself

Total productive maintenance (TPM) has become the largest part of the MORAVA program. Production shops are participating in this TPM program, especially by carrying out independent maintenance, which includes cleaning, adjusting, lubricating, and other simple activities. Machine operators perform these after receiving step-by-step training. Traditionally high levels of machine repair abilities among the workers contributed to the success of the TPM program. It was important that the machine operators were able to do the following:

- Distinguish normal from abnormal operation of a machine
- Secure normal conditions for the operation of a machine
- Correct irregularities in the working of a machine

According to the program, implementation of independent maintenance was divided into several stages. BARUM Continental uses the TPM concepts that were defined in Japan and uses the so-called seven-step approach to carry out independent maintenance:

1. Implementation of the initial cleaning
2. Removal of sources that cause trash accumulation
3. Generation of standards for cleaning, inspection, and lubrication
4. Training in general inspection and the creation of inspection procedures
5. Carrying out independent inspection
6. Organization and control of the workplace with respect to the overall efficiency of equipment
7. Improvement of the complete workplace

The TPM team led by the company's TPM coordinator played a significant role. This team successfully planned, prepared, and supported the implementation of TPM within the entire company. It took three months, during which time the environment for a successful implementation and extension of TPM was being established. Also during this time, the company's management presented its recommendations regarding the introduction of the TPM program. At the same time, it held seminars about TPM, prepared newsletters, and produced a video. Every worker who participated in the TPM program was informed about the advantages of TPM and how it was to be implemented. This step was very important because it helped to overcome possible misunderstandings during the introduction of the new work scheme. The initial selection of a pilot area (production of truck tires) in which methodologies were tested and valuable experiences gained made the implementation of TPM easier. The tasks of the TPM team included specification of the basic rules, development of handbooks and manuals, and preparation of the schedule for further developments.

The coefficient of overall equipment effectiveness (OEE) was chosen as the measurable parameter for the evaluation of the utilization of machines. This coefficient was monitored and evaluated for every machine that was included in the TPM program. After testing the method during the pilot project, the TPM method was broadened to cover the entire production process.

Each organizational unit introducing TPM had its own plan for independent maintenance. The completion of the plan was supported by a coordinator at each specific workplace. The requirements connected with the accomplishment of individual steps within the framework of independent maintenance were reviewed by independent auditors.

By the end of 1997, the first step of independent maintenance was implemented on the most important machines, and some of the pilot area machines had already reached step 3. The application of the TPM principles of the first phase improved the layout and cleanliness of machines and workplaces. Great attention was paid to routine maintenance by machine operators, who became more involved in activities such as the identification of irregularities in the machines and the replacement of tools or autonomous lubrication. The savings achieved by using the TPM method were a function of the increase of productivity on each significant production machine. This is illustrated in Fig. 2.13.6.

Since 1998, the company has been gaining experience with the second phase of independent maintenance (steps 4 and 5), which involves training machine operators and developing their abilities to repair selected types of irregularities and defects.

RESULTS AND FUTURE ACTIONS

BARUM Continental's focus on industrial engineering, with the emphasis on increasing productivity and quality from the very beginning of the transformation process, has been reflected in the company's results. Figures 2.13.7 and 2.13.8 illustrate the positive developments of economic and business parameters. The productivity growth since the start of the joint venture is depicted in Fig. 2.13.7. The graph shows an unequivocally positive trend, which proves that the transformation process was successful and that the future is promising. Figure 2.13.8 shows the

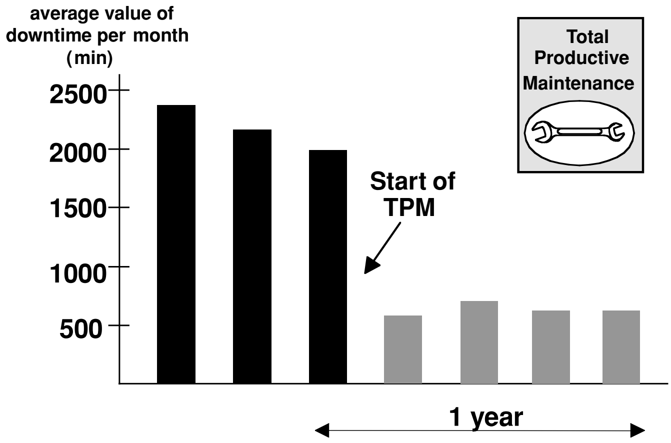

FIGURE 2.13.6 Downtime of an important machine before and after the implementation of TPM.

growth in sales in the 1990s, which bears witness to the company's growing business success. Thanks to these results, BARUM Continental ranks among the most dynamically developing companies, not only in the Czech republic, but also within the European economic domain.

BARUM Continental became the largest tire producer in Central Europe because of the positive results achieved from 1993 to 1997. The company's development has not yet been completed. The company is launching another ambitious plan that includes doubling its sales within the next two years. It expects to produce more than 11 million tires a year.

This case study was intended to show that achieving similar results is dependent on a more efficient production system that uses industrial engineering methods. BARUM Continental is developing and improving industrial production and administrative and business processes so that the coming years will continue its positive trends and share of the market. The next project aims to set up a "team company," which will extend BARUM Continental's success into the first years of the twenty-first century. In order to achieve these goals, the company is implementing and developing industrial engineering, employing the concepts of a fractal factory, and applying world-class methods.

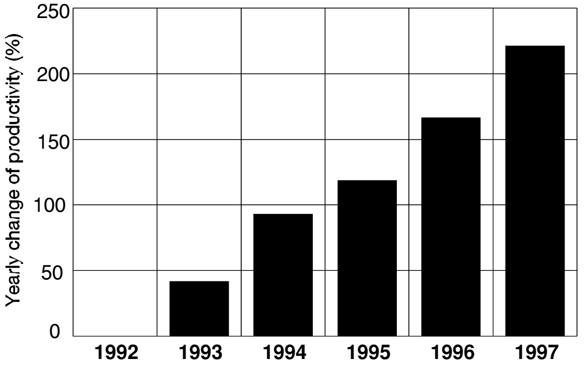

FIGURE 2.13.7 Productivity development compared to 1992.

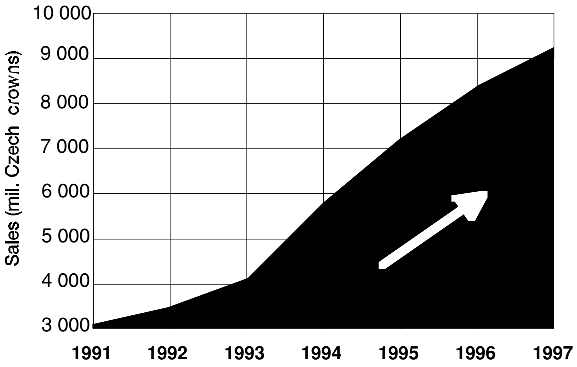

FIGURE 2.13.8 Sales development.

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BIOGRAPHIES

Milan Vytlačil is a management consultant specializing in company transformations using industrial engineering methods. He is a professor of Management at the Technical University of Brno in the Czech Republic. After receiving his M.E. degree at the Technical University in Liberec, Professor Vytlačil held a variety of technical and managerial positions in the automotive industry, which included manager of the industrial engineering department in the Škoda Auto Company (Volkswagen Group). Professor Vytlačil is cofounder and president of the Institute of Industrial Engineering (IPI), a consulting company in Liberec, and has authored several books about industrial engineering.

Ivan Mašín is an industrial engineering consultant and instructor specializing in JIT techniques and is an assistant professor of Industrial Engineering at the Faculty of Management in Zlin, Czech Republic. Dr. Mašín graduated from the Technical University in Liberec, where he also finished his doctoral studies. He worked in the industrial engineering department at the Škoda Auto Company (Volkswagen Group). He is the cofounder and vice president of the Institute of Industrial Engineering in Liberec (IPI). His specialization includes TPM, continuous improvement, kanban, and teamwork. He is the coauthor of several books and training materials on industrial engineering.

Petr Sehnal has been production manager and CEO of the BARUM Continental truck tire production plant. He has over 25 years of experience in the tire industry, where he has held both shop-floor and managerial positions. Since graduating as an electronics and industrial engineer from the Technical University in Brno, he has worked as an industrial engineering department manager and production manager at BARUM Continental in Otrokovice (Czech Republic), the largest tire producer in central Europe. In 1999, he became the managing director and CEO in the new joint venture, Continental Matador, in Puchov (Slovak Republic).

SECTION 3

ENGINEERING ECONOMICS

CHAPTER 3.1

PRINCIPLES OF ENGINEERING ECONOMY AND THE CAPITAL ALLOCATION PROCESS*

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As is the case with other types of capital allocation decisions, *engineering economy* rests on the proposition that refusal to expend scarce resources is rarely, if ever, the most prudent course of action. Rather, the problem is one of choosing from among a variety of investment alternatives to satisfy the decision makers' intermediate and longer-term objectives. The operative word is *economy,* and the essential ingredient in economy is consideration of the economic consequences of alternatives over a measured period of time—the planning horizon. This chapter is dedicated to the principles and procedures for evaluating the economic consequences of engineering plans, programs, designs, policies, and the like. The effects of income taxes and relative price changes (inflation) are also considered.

FUNDAMENTAL PRINCIPLES

Before developing the mathematical models appropriate to evaluating capital proposals, it will be useful to identify the fundamental principles that give rise to the rationale of capital allocation. Moreover, some of these principles lead directly to the quantitative techniques developed subsequently.

1. *Only feasible alternatives should be considered.* The capital budgeting analysis begins with determination of all feasible alternatives, since courses of action that are not feasible, because of certain contractual or technological considerations, are properly excluded.
2. *Using a common unit of measurement (a common denominator) makes consequences commensurable.* All decisions are made in a single dimension, and money units—dollars, francs, pesos, yen, and so forth—seem to be most generally suitable. Of course, not all consequences may be evaluated in money terms. (See principle 9.)
3. *Only differences are relevant.* The prospective consequences that are common to all contending alternatives need not be considered in an analysis because including them affects all alternatives equally.

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* Portions of the material included in this chapter have been adapted from G. A. Fleischer, *Introduction to Engineering Economy,* PWS Publishing Company, 1994. It is reproduced here by permission of the publisher.

4. *All sunk costs are irrelevant to an economic choice.* A *sunk cost* is an expense or a revenue that has occurred before the decision. All events that take place before a decision are common to all the alternatives, so sunk costs are not differences among alternatives.
5. *All alternatives must be examined over a common planning horizon.* The *planning horizon* is the period of time over which the prospective consequences of various alternatives are assessed. (The planning horizon is often referred to as the *study period* or *period of analysis.*)
6. *Criteria for investment decisions should include the time value of money and related problems of capital rationing.*
7. *Separable decisions should be made separately.* This principle requires the careful evaluation of all capital-allocation problems to determine the number and type of decisions to be made.
8. *The relative degrees of uncertainty associated with various forecasts should be considered.* Because estimates are only predictions of future events, it is probable that the actual outcomes will differ to a greater or lesser degree from the original estimates. Formal consideration of the type and degree of uncertainty ensures that the quality of the solution is evident to those responsible for capital-allocation decisions.
9. *Decisions should give weight to consequences that are not reducible to monetary units.* The irreducible as well as monetary consequences of proposed alternatives should be clearly specified to give managers of capital all reasonable data on which to base their decisions.

EQUIVALENCE AND THE MATHEMATICS OF COMPOUND INTERESTS

A central notion in engineering economy is that cash flows (that is, the receipt or payment of an amount of money) that differ in magnitude but occur at different points in time may be *equivalent.* This equivalence is a function of the appropriate interest rate per unit time and the relevant time interval. Mathematical relationships describing the equivalence property under a variety of conditions are described in the remainder of this section.

Useful Conventions

The following conventions will be used in this chapter.

Cash Flow Diagrams. In the literature of engineering economy, cash flow diagrams are frequently used to illustrate the amount and timing of cash flows. Generally, a horizontal bar or line is used to represent time, and vertical vectors (arrows) are used to represent positive or negative cash flows at the appropriate points in time. These cash flow diagrams are illustrated later in Fig. 3.1.1. The shaded arrows in the right-hand portion of the figure represent cash flowing continuously and uniformly throughout the indicated period(s).

Functional Notation. As the algebraic form of the various equivalence factors can be complex, it is useful to adopt a standardized format that is easily learned and has a mnemonic connotation. The format that is in general use* is of the form

$$(X|Y, i, N)$$

which is read as "to find the equivalent amount X given amount Y, the interest rate i and the number of compounding or discounting periods N."

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* This is the functional notation recommended in *Industrial Engineering Terminology,* revised edition, Industrial Engineering and Management Press, Industrial Engineering Institute, Norcross, GA, 1991.

Discrete Cash Flows—End of-Period Compounding

Assume that a cash flow A_j occurs at end of period j. Interest is compounded or discounted at the end of each period at rate i period. The interest rate i is constant over $j = 1, 2, \ldots, N$. The periods are of equal duration.

Single Cash Flows. Consider a single cash flow P to be invested at the beginning of a time series of exactly N periods. Let F represent the *equivalent future value* of P as measured at the end of N periods hence, assuming that interest is compounded at the end of each and every period at interest rate i. Then,

$$F = P(1 + i)^N = P(F/P, i, N) \tag{3.1.1}$$

It follows immediately that, given a future amount F flowing at the end of N periods hence, the *equivalent present value* P is given by

$$P = F(1 + i)^{-N} = F(P/F, i, N) \tag{3.1.2}$$

The growth multiplier as shown in Eq. (3.1.1), $(1 + i)^N$, is known in the literature of engineering economy as the (*single payment*) *compound amount factor.* The discounting multiplier shown in Eq. (3.1.2) is known as the (*single payment*) *present worth factor.*

The cash flow diagrams, algebraic forms, and functional forms for these two factors will be shown in Fig. 3.1.1. Tabulated values of $i = 10$ percent and for various values of N are given in Table 3.1.6 at the end of this chapter.

Examples. A sum of $1000 is invested in a fund that earns interest at the rate of 1 percent per month, compounded monthly. To determine the value of the fund after 24 months, using Eq. (3.1.1):

$$F = \$1000(1.01)^{24} = \$1269.73$$

A certain investment is expected to yield a return of $100,000 exactly 8 years in the future. Assuming a discount rate of 10 percent per year, what is the equivalent present value? Using Eq. (3.1.2):

$$P = \$100{,}000(1.10)^{-8} = \$46{,}651$$

rom Eq. (3.1.1):

$$\$2 = \$1(1.08)^{-N}$$

$$N = \ln 2/\ln 1.08 \simeq 9 \text{ periods}$$

An investment of $10,000 yields a return of $20,000 five years later. What (annual) rate of return was earned? From Eq. (3.1.1):

$$\$20{,}000 = \$10{,}000(1 + i)^5$$

$$i = (\$20{,}000/\$10{,}000)^{1/5} - 1 = 14.87 \text{ percent}$$

Uniform Series (Annuity). Consider a uniform series of cash flows A occurring at the end of each of N consecutive periods. That is, $A_j = A$ for $j = 1, 2, \ldots, N$. The equivalent future value F at the end of N periods is given by

$$F = A\left[\frac{(1 + i)^N - 1}{i}\right] = A(F/A, i, N) \tag{3.1.3}$$

The factor in brackets is known as the (*uniform series*) *compound amount factor.* To find A given F:

$$A = F\left[\frac{i}{(1+i)^N - 1}\right] = F(A/F, i, N) \tag{3.1.4}$$

The factor in brackets is known as the *sinking fund factor.*

The equivalent present value of this uniform series is given by

$$P = A\left[\frac{(1+i)^N - 1}{i(1+i)^N}\right] = A(P/A, i, N) \tag{3.1.5}$$

The factor in brackets is known as the (*uniform series*) *present worth factor.* To find A given P:

$$A = P\left[\frac{i(1+i)^N}{(1+i)^N - 1}\right] = P(A/P, i, N) \tag{3.1.6}$$

The factor in brackets is known as the *capital recovery factor.*

As before, the appropriate cash flow diagrams, algebraic forms, and functional forms will be shown in Fig. 3.1.1. Tabulated values for $i = 10$ percent are given in Table 3.1.6.

Examples. A sum of $10,000 is invested at the end of each period for 15 periods. What is the amount in the fund after the 15th payment has been made? (A 10 percent interest rate is assumed for all the following examples.) From Eq. (3.1.3):

$$\begin{aligned} F &= \$10{,}000(F/A, 10\%, 15) \\ &= \$10{,}000(31.772) = \$317{,}720 \end{aligned}$$

(Note that the value for the compound amount factor has been taken from Table 3.1.6.) How much must be invested at the end of each year for 15 years in order to have $20,000 in the fund after the 15th payment? From Eq. (3.1.4):

$$\begin{aligned} A &= \$20{,}000(A/F, 10\%, 15) \\ &= \$20{,}000(0.0315) = \$630 \end{aligned}$$

How much must be invested today in order to yield returns of $2500 at the end of each and every year for 8 years? From Eq. (3.1.5):

$$\begin{aligned} P &= \$2500(P/A, 10\%, 8) \\ &= \$2500(5.335) = \$13{,}337 \end{aligned}$$

Certain equipment costs $50,000, will be used for 5 years, and will have no value at the end of 5 years. What is the equivalent annual (end-of-year) cost? From Eq. (3.1.6):

$$\begin{aligned} A &= \$50{,}000(A/P, 10\%, 5) \\ &= \$50{,}000(0.2638) = \$13{,}190 \end{aligned}$$

Arithmetic Gradient Series. Let $A_j = (j - 1)G$ for $j = 1,2, \ldots ,N,$ where G represents the amount of increase or decrease in cash flow from one period to the next. This results in an arithmetic series of the cash flows of the form $0,G,2G, \ldots ,(N - 1)\,G$ for periods $1,2, \ldots ,N,$ respectively. Given the gradient $G,$ the equivalent present value is given by

$$P = G\left[\frac{(1+i)^N - iN - 1}{i^2(1+i)^N}\right] = G(P/G, i, N) \tag{3.1.7}$$

and the equivalent uniform series is given by

$$A = G\left[\frac{(1+i)^N - iN - 1}{i(1+i)^N - i}\right] = G(A/G, i, N) \tag{3.1.8}$$

Again, the appropriate cash flow diagrams, algebraic forms, and functional forms are shown later in Fig. 3.1.1. Representative tabulated values are given in Table 3.1.6 for (P/G, 10%, N) and (A/G, 10%, N).

Example. Costs of manufacturing are assumed to be $100,000 the first year and to increase by $10,000 in each of the years 2 through 7. If interest is at 10 percent per year, determine the equivalent present value of these costs. Using Eqs. (3.1.5) and (3.1.7) and taking the appropriate factor values from Table 3.1.6:

$$P = \$100{,}000(P/A,\ 10\%, 7) + \$10{,}000(P/G,\ 10\%, 7)$$

$$= \$100{,}000(4.868) + \$10{,}000(12.763) = \$614{,}430$$

Note: This analysis assumes that all cash flows occur at end of year.

Geometric Gradient Series. Consider a series of cash flows $A_1, A_2, \ldots, A_N$ where the A_j's are related as follows:

$$A_j = A_{j-1}(1+g) = A_1(1+g)^{j-1} \tag{3.1.9}$$

where g represents the rate of increase or decrease in cash flows from one period to the next. With cash flows discounted at rate i per period, the equivalent present value of the geometric series is given by

$$P = A_1\left[\frac{1 - (1+g)^N(1+i)^{-N}}{i - g}\right] = A_1(P/A_1, i, g, N) \tag{3.1.10}$$

As N approaches infinity, this series is convergent if $g < i$. Otherwise ($g \geq i$) if the series is divergent.

Example. Manufacturing costs are expected to be $100,000 in the first year, increasing by 5
Find the equivalent present value of these cash flows
end-of-year cash flows. Using Eq. (3.1.10):

$$P = \$100{,}000(P/A_1, 10\%, 5\%, 7)$$

$$= \$100{,}000(5.5587) = \$555{,}870$$

Effective and Nominal Interest Rates

An interest rate is meaningful only if it is related to a particular period of time. Nevertheless, the "time tag" is frequently omitted in speech because it is usually understood in context. If someone reports earnings of 6 percent on investments, for example, it is implied that the rate of return is *per year.* However, in many cases the interest-rate period is a week, a month, or some other interval of time, rather than the more usual year (per annum). At this point it would be useful to examine the process whereby interest rates and their respective time tags are made commensurate.

As before, let i represent the *effective* interest rate per period. Let the period be divided into M subperiods of equal length. If interest is compounded at the end of each subperiod at rate i_s per subperiod, then the relationship between the effective interest rates per period and per subperiod is given by

$$i = (1 + i_s)^M - 1 \tag{3.1.11}$$

The *nominal* interest rate per period, r, is simply the effective interest rate per subperiod times the number of subperiods, or

$$r = Mi_s \tag{3.1.12}$$

Period and Subperiods

Example. It is often necessary to compare interest rates over a common time interval. Consider, for example, the case of consumer credit: a major oil company or bank charge card for which interest is compounded monthly at rate 1.5 percent of the unpaid balance. Here $i_s = 0.015$ and $M = 12$. The *nominal* rate per annum, by Eq. (12) is $12 \times 0.015 = 0.18$. The *effective* rate per annum, by Eq. (3.1.11) is

$$i = (1.015)^{12} - 1 = 0.1956$$

Periods and Superperiods. Consider a uniform series of cash flows A occurring at regular intervals. Specifically, the cash flows occur every M periods, with the first cash flow occurring at the end of period m and the last cash flow occurring at the end of period n, where $1 \leq m \leq n \leq N$. There are exactly $[(n - m)/M] + 1$ cash flows in M periods, where M is integer-valued, with the start of the first superperiod at the end of period $m - M$. The equivalent present value of this uniform series of cash flows is given by

$$P = A\left\{\frac{(1+i)^{n-m+M} - 1}{(1+i)^n[(1+i)^M - 1]}\right\} \tag{3.1.13}$$

For example, consider major overhaul expenses of \$20,000 each occurring at the end of year 5 and continuing, every 2 years, up to and including year 13. ($A_j = -\$20{,}000$ for $j = 5,7,9,11,13$.) Assuming a 10 percent discount rate:

$$P = \$20{,}000\left\{\frac{(1.10)^{13-5+2} - 1}{(1+1)^{13}[(1.10)^2 - 1]}\right\}$$

$$= \$20{,}000(1.19834) = \$43{,}967$$

Assuming that the number of subperiods, at the end of which interest is compounded or discounted, becomes infinitely large, the effective interest rate per period is

$$i = \lim_{M \to \infty}\left\{\left[\left(1 + \frac{1}{M/r}\right)^{M/r}\right]^r - 1\right\} = e^r - 1 \tag{3.1.14}$$

where e is the base of the natural (Napierian) logarithm system and is approximately equal to 2.71828.

Assume that a total of $\overline{A}$ dollars flows over one interest period, with $\overline{A}/M$ flowing at the end of each and every one of the M subperiods within the period. As before, the *effective* interest rate is i per period and the nominal rate is r per period. Interest is compounded at effective rate $i_s = r/M$ per subperiod. Let A represent the equivalent value at the end of the period:

$$A = (\overline{A}/M)(F/A, i_s, M)$$

As the number of subperiods (M) becomes infinitely large, it may be shown that

$$A = \overline{A}\left[\frac{e^r - 1}{r}\right] = \overline{A}\left[\frac{i}{\ln(1+i)}\right] \tag{3.1.15}$$

The value in brackets is known as the *funds flow conversion factor* because it has the effect of converting a continuous cash flow (during the period) to a discrete cash flow (at the end of the period). The funds flow conversion factor is useful in modifying the end-of-period factors, previously discussed, to accommodate the "continuous" assumptions. To illustrate, consider the factor for determining the equivalent present value of a cash flow ($\overline{F}$) flowing continuously and uniformly during the Nth period hence. Combining Eqs. (3.1.2) and (3.1.15):

$$\begin{aligned} P &= \overline{F}\left[\frac{i}{\ln(1+i)}\right](1+i)^{-N} \\ &= \overline{F}(P/\overline{F}, i, N) \end{aligned} \tag{3.1.16}$$

Similarly,

$$\begin{aligned} P &= \overline{A}\left[\frac{i}{\ln(1+i)}\right]\left[\frac{(1+i)^N - 1}{i(1+i)^N}\right] \\ &= \overline{A}(P/\overline{A}, i, N) \end{aligned} \tag{3.1.17}$$

For ease of reference, all of the equivalence models described previously are summarized in Fig. 3.1.1. Models for *discrete cash flows* are shown in Fig. 3.1.1(*a*) under the two compounding conventions: (1) *end-of-period* compounding at effective interest rate i and (2) *continuous* compounding at nominal interest rate r. Models for *continuous cash flows* are shown in Fig. 3.1.1(*b*) under the assumption of continuous compounding at (1) effective interest rate i and (2) nominal interest rate r.

METHODS FOR SELECTING AMONG ALTERNATIVES

A variety of methods are used to evaluate alternative investments. Associated with each is a *statistic,* that is, a "figure of merit," and a *decision rule* that is used to select from among alternatives on the basis of the statistics. These are presented briefly here for a set of evaluation methods that are most commonly used in engineering economy.

Present Worth (Net Present Value)

Present worth (PW) and *net present value* (NPV) are equivalent terms. The former is widely used in the literature of engineering economy; the latter is common to the literature of finance and accounting.

Present Worth of a Proposed Investment. The *present worth* is the equivalent present value of the cash flows generated by the proposed investment over a specified time interval (planning horizon N) with discounting at a specified interest rate i. One of several algebraic expressions for PW, assuming end-of-period cash flows A_j and end-of-period discounting at rate i, is

$$PW = \sum_{j=0}^{N} A_j(1+i)^{-j} \tag{3.1.18}$$

The *planning horizon* represents that period of time over which the proposed project is to be evaluated. It should be of sufficient duration to reflect all significant differences between the project and alternative investments. The discount rate i is the *minimum attractive rate of return,* that is, the rate of return that could be expected if the funds to be invested in the proposed project were to be invested elsewhere.

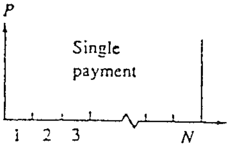
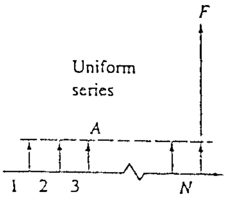
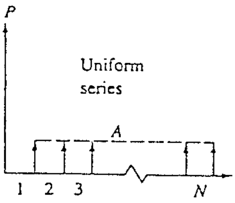
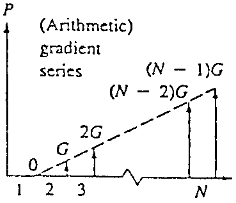
END-OF-PERIOD COMPOUNDING EFFECTIVE INTEREST RATE (i)		CONTINUOUS COMPOUNDING NOMINAL INTEREST RATE (r)
1* $F = P(F/P, i, N)$ $= P(1+i)^N$ 3* $P = F(P/F, i, N)$ $= F(1+i)^{-N}$	 P Single payment 1 2 3 N	$P = F(P/F, r, N)$ $= Fe^{-rN}$
5* $F = A(F/A, i, N)$ $= A\left[\frac{(1+i)^N - 1}{i}\right]$ 7* $A = F(A/F, i, N)$ $= F\left[\frac{i}{(1+i)^N - 1}\right]$	 F Uniform series A 1 2 3 N	6 $F = A(F/A, r, N)$ $= A\left[\frac{e^{rN} - 1}{e^r - 1}\right]$ 8 $A = F(A/F, r, N)$ $= F\left[\frac{e^r - 1}{e^{rN} - 1}\right]$
9* $P = A(P/A, i, N)$ $= A\left[\frac{(1+i)^N - 1}{i(1+i)^N}\right]$ 11* $A = P(A/P, i, N)$ $= P\left[\frac{i(1+i)^N}{(1+i)^N - 1}\right]$	 P Uniform series A 1 2 3 N	10 $P = A(P/A, r, N)$ $= A\left[\frac{e^{rN} - 1}{e^{rN}(e^r - 1)}\right]$ 12 $A = P(A/P, r, N)$ $= P\left[\frac{e^{rN}(e^r - 1)}{e^{rN} - 1}\right]$
13* $P = G(P/G, i, N)$ $= G\left[\frac{(1+i)^N - iN - 1}{i^2(1+i)^N}\right]$ 15* $A = G(A/G, i, N)$ $= G\left[\frac{(1+i)^N - iN - 1}{i(1+i)^N - i}\right]$	 P (Arithmetic) gradient series (N − 1)G (N − 2)G 2G G 0 1 2 3 N	14 $P = G(P/G, r, N)$ $= G\left[\frac{e^{rN} - Ne^r + N - 1}{e^{rN}(e^r - 1)^2}\right]$ 16 $A = G(A/G, i, N)$ $= G\left[\frac{e^{rN} - Ne^r + N - 1}{(e^r - 1)(e^{rN} - 1)}\right]$

FIGURE 3.1.1 Cash flow models and mathematical models for selected compound interest factors: (*a*) Discrete cash flows.

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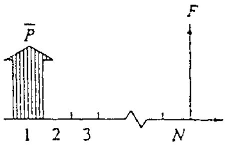
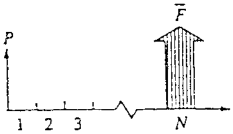
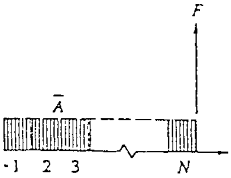
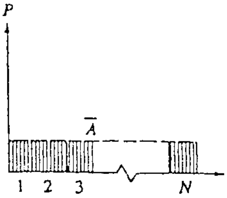
CONTINUOUS COMPOUNDING EFFECTIVE INTEREST RATE (i)		CONTINUOUS COMPOUNDING NOMINAL INTEREST RATE (r)
17 $F = \bar{P}(F/\bar{P}, i, N)$ $= \bar{P}\left[\frac{i(1+i)^{N-1}}{\ln(1+i)}\right]$		
19* $P = \bar{F}(P/\bar{F}, i, N)$ $= \bar{F}\left[\frac{i(1+i)^{-N}}{\ln(1+i)}\right]$		20 $P = \bar{F}(P/\bar{F}, r, N)$ $= \bar{F}\left[\frac{e^{r}-1}{re^{rN}}\right]$
21* $F = \bar{A}(F/\bar{A}, i, N)$ $= \bar{A}\left[\frac{(1+i)^{N}-1}{\ln(1+i)}\right]$ 23 $\bar{A} = F(\bar{A}/F, i, N)$ $= F\left[\frac{\ln(1+i)}{(1+i)^{N}-1}\right]$		22 $F = \bar{A}(F/\bar{A}, r, N)$ $= \bar{A}\left[\frac{e^{rN}-1}{r}\right]$ 24 $\bar{A} = F(\bar{A}/F, r, N)$ $= F\left[\frac{r}{e^{rN}-1}\right]$
25* $P = \bar{A}(P/\bar{A}, i, N)$ $= \bar{A}\left[\frac{(1+i)^{N}-1}{(1+i)^{N}\ln(1+i)}\right]$ 27 $\bar{A} = P(\bar{A}/P, i, N)$ $= P\left[\frac{(1+i)^{N}\ln(1+i)}{(1+i)^{N}-1}\right]$		26 $P = \bar{A}(P/\bar{A}, r, N)$ $= \bar{A}\left[\frac{e^{rN}-1}{re^{rN}}\right]$ 28 $\bar{A} = P(\bar{A}/P, r, N)$ $= P\left[\frac{re^{rN}}{e^{rN}-1}\right]$

(*Continued*) Cash flow models and mathematical models for selected compound interest factors: (*b*) Continuous cash flows.

Present Worth of the "Do Nothing" Alternative. Let P represent the initial investment in a proposed project. If P were to be invested elsewhere, rather than in the proposed project, then this "do nothing" alternative would yield $P(1+i)^N$, assuming compounding at rate i for N periods. The present worth of this course of action is zero, as can be seen by

$$\begin{aligned}\text{PW} &= A_0 + A_N(1+i)^{-N}\\ &= -P + P(1+i)^N(1+i)^{-N} = 0\end{aligned}$$

Comparing the proposed investment with the do nothing alternative, it follows that the investment is economically attractive (preferred to doing nothing) if its PW > 0. The do nothing alternative is sometimes known as *alternative zero.* Here, PW(∅) = 0.

Multiple (More Than Two) Alternatives. We have seen that given two alternatives, (1) the proposed project and (2) do nothing, the "invest" decision is indicated if PW > 0. But suppose that there are more than two alternatives under consideration. In this case, the PWs of each of the alternatives are rank-ordered, and the *alternative yielding the maximum PW is to be preferred* (in an economic sense only, of course). To illustrate, consider the four mutually exclusive alternatives summarized in Table 3.1.1. Present worths have been determined using Eq. (3.1.18) and assuming $i = 20$ percent. As noted in the table, the correct rank ordering of the set of alternatives is IV > II > III > ∅ > I.

It is not necessary to adjust the PW statistic for differences in initial cost, because any funds invested elsewhere yield a PW of zero. In our example, consider alternatives II and III. Initial costs are \$1000 and \$1100, respectively. Alternative II may be viewed as requiring \$1000 in the project (yielding PW of \$258) and \$100 elsewhere (yielding PW of \$0). The total PW(II) = \$258. This may now be compared directly with alternative III: PW(III) = \$242. Each alternative accounts for a total investment of \$1100.

Annual Worth (Equivalent Uniform Annual Cost)

The *annual worth* (AW) is the uniform series over N periods equivalent to the present worth at interest rate i. It is a weighted average periodic worth, weighted by the interest rate. Mathematically,

$$\text{AW} = (\text{PW})(A/P, i, N) \tag{3.1.19}$$

If $i = 0$ percent, then AW is simply the average cash flow per period, that is,

$$\text{AW} = (1/N)\sum_{j=0}^{N} A_j$$

By convention, this is known as the *annual* worth method, although the period may be a week, a month, or the like. This method is most often used with respect to *costs,* and in such cases it is known as the equivalent uniform annual cost (EUAC) method.

TABLE 3.1.1 Cash Flows for Four Mutually Exclusive Alternatives

	Assume $i = 20\%$			
End of period	Alternative I	Alternative II	Alternative III	Alternative IV
0	–\$1000	–\$1000	–\$1100	–\$2000
1–10	0	300	320	520
10	4000	0	0	0
Net cash flow	\$3000	\$2000	\$2100	\$3500
PW	–\$354	\$258	\$242	\$306
AW	–\$85	\$62	\$58	\$73
FW	–\$2192	\$1596	\$1496	\$1894

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The decision rule applicable to PW is also applicable for AW (and EUAC). That is, a proposal is preferred to the do nothing alternative if AW > 0, and multiple alternatives may be rank-ordered on the basis of declining AW (or increasing EUAC). Given any pair of alternatives, say, X and Y, if $\text{PW}(X) > \text{PW}(Y)$, then $\text{AW}(X) > \text{AW}(Y)$. This is so because $(A/P, i, N)$ is a constant for all alternatives as long as i and N remain constant.

The annual worth method is illustrated in Table 3.1.1. Note that the ranking of alternatives is consistent with that of the PW method: IV > II > III > ∅ > I.

Future Worth

In the *future worth* (FW) method, all cash flows are converted to a single equivalent value at the end of the planning horizon: period N. Mathematically:

$$\text{FW} = (\text{PW})(F/P, i, N)$$

The decision rule applicable to PW is also applicable to FW. A set of mutually exclusive investment opportunities may be rank-ordered by using either PW, AW, or FW. The results will be consistent. The future worth method is also illustrated in Table 3.1.1.

Rate of Return

Internal Rate of Return. The internal rate of return (IRR), often known simply as the rate of return (RoR), is that interest rate i^* for which the net present value of all project cash flows is zero. When all cash flows are discounted at rate i^*, the equivalent present value of all project benefits exactly equals the equivalent present value of all project costs. One mathematical definition of IRR is the rate i^* that satisfies the equation

$$\sum_{j=0}^{N} A_j \,(1 + i^*)^{-j} \equiv 0 \tag{3.1.20}$$

his formula assumes discrete cash flows A_j and end-of-period discounting in periods $j = 1, , \ldots, N$.

The discount rate used in present worth calculations is the opportunity cost—a measure of the
that could be earned on capital if it were invested elsewhere. Thus a given proposed proj-
should be economically attractive if, and only if, its internal rate of return exceeds the cost of
forgone as measured by the firm's minimum attractive rate of return (MARR).
hat is, an increment of investment is justified if, for that proposal, IRR > MARR.

Multiple Alternatives. Unlike the PW/AW/FW methods, mutually exclusive projects may *not* be rank-ordered on the basis of their respective IRRs. Rather, an incremental procedure must be implemented. Alternatives must be considered pairwise, with decisions made about the attractiveness of each increment of investment. As shown in Table 3.1.2, we conclude that the order would be IV > II > ∅ > I. These results are consistent with those found by the PW/AW/FW methods.

Multiple Solutions. Consider the end-of-period model described by Eq. (20):

$$\sum_{j=0}^{N} A_j \,(1 + i^*)^{-j} \equiv 0$$

This expression may also be written as

$$A_0 + A_1x + A_2x^2 + \ldots + A_Nx^N = 0 \tag{3.1.21}$$

TABLE 3.1.2 (Internal) Rate of Return Analysis of Alternatives from Table 3.1.1

Step	Comparison of alternatives	Cash flows (A_j) A_0	A_1–A_{10}	A_{10}	Incremental rate of return, %	Conclusion (MARR = 20%)
1	$\varnothing \rightarrow$ I	–\$1000	0	4000	14.9	I < $\varnothing$
2	$\varnothing \rightarrow$ II	–1000	300	0	27.3	II > $\varnothing$
3	$\varnothing \rightarrow$ III	–1100	320	0	26.3	III > $\varnothing$
4	$\varnothing \rightarrow$ IV	–2000	550	0	24.4	IV > $\varnothing$
5	II → III	–100	20	0	15.1	III < II
6	II → IV	–1000	250	0	21.4	IV > II

where $x = (1 + i^*)^{-1}$. Solving for x leads to i^*, so we want to find the roots x of this Nth-order polynomial expression. Only the real, positive roots are of interest, of course, because any meaningful values of i^* must be real and positive. There are many possible solutions for x, however, depending upon the signs and magnitudes of the cash flows A_j. Multiple solutions for x—and, by extension, i^*—are possible. In those instances where multiple IRRs are obtained, it is recommended that the PW method rather than the rate of return method be used.

Benefit-Cost Ratio

The benefit-cost ratio method is widely used in the public sector.

Benefit-Cost Ratio and Acceptance Criterion. The essential element of the benefit-cost ratio method is almost trivial, but it can be misleading in its simplicity. An investment is justified only if the incremental benefits B resulting from it exceed the resulting incremental costs C. Of course, all benefits and costs must be stated in equivalent terms, that is, with measurement at the same point(s) in time. Normally, both benefits and costs are stated as present value or are annualized by using compound interest factors as appropriate. Thus,

$$\text{B:C} = \frac{\text{PW (or AW) of all benefits}}{\text{PW (or AW) of all costs}} \tag{3.1.22}$$

Clearly, if benefits must exceed costs, the ratio of benefits to costs must exceed unity. That is, if $B > C$, then $B{:}C > 1.0$. This statement of the *acceptance criterion* is true only if the incremental costs C are positive. It is possible, when evaluating certain alternatives, for the incremental costs to be negative, that is, for the proposed project to result in a reduction of costs. Negative benefits arise when the incremental effect is a reduction in benefits. In summary,

For $C > 0$, if $B{:}C > 1.0$, accept; otherwise reject.

For $C < 0$, if $B{:}C > 1.0$, reject; otherwise accept.

Multiple Alternatives. Like the rate of return method, the proper use of the benefit-cost ratio method requires incremental analysis. Mutually exclusive alternatives *should not be rank-ordered on the basis of benefit-cost ratios.* Pairwise comparisons are necessary to test whether increments of costs are justified by increments of benefits.

To illustrate, consider two alternative projects U and T.

Comparison	Present Worths Benefits, \$	Costs, \$	$B{:}C$	Conclusion
$\varnothing \rightarrow T$	700,000	200,000	3.50	$T > \varnothing$
$\varnothing \rightarrow U$	1,200,000	600,000	2.00	$U > \varnothing$
$\varnothing \rightarrow U$	500,000	400,000	1.25	$U > T$

On the basis of benefit-cost ratios, it is clear that both T and U are preferred to the do nothing alternative ($\varnothing$). Moreover, the *incremental* analysis indicates that U is preferred to T since the incremental $B{:}C$ (= 1.25) exceeds unity.

It will be noted here that PW analysis would yield the same result: PW(T) = \$500,000 and PW(U) = \$600,000. It may be shown that this result obtains in general. That is, for any number of mutually exclusive alternatives, ranking based on *proper* use of the benefit-cost ratio method using *incremental* analysis will always yield the same rank order resulting from proper use of the present worth method.

Payback

The payback method is widely used in industry to determine the relative attractiveness of investment proposals. The essence of this technique is the determination of the *number of periods required to recover an initial investment.* Once this has been done for all alternatives under consideration, a comparison is made on the basis of respective payback periods.

Payback, or *payout,* as it is sometimes known, is the number of periods required for cumulative benefits to equal cumulative costs. Costs and benefits are usually expressed as cash flows, although discounted present values of cash flows may be used. In either case, the payback method is based on the assumption that the relative merit of a proposed investment is measured by this statistic. The smaller the payback (period), the better the proposal.

(*Undiscounted*) *payback* is that value of N^* such that

$$P = \sum_{j=1}^{N^*} A_j \tag{3.1.23}$$

where P is the initial investment and A_j is the cash flow in period j. *Discounted payback,* used much less frequently, is that value of N^* such that

$$P = \sum_{j=1}^{N^*} A_j(1+i)^{-j} \tag{3.1.24}$$

The principal objection to the use of payback as a primary figure of merit is that all consequences beyond the end of the payback periods are ignored. This may be illustrated by a simple example. Consider two alternatives V and W. The discount rate is 10 percent and the planning horizon is 5 years. Cash flows and the relevant results are as follows:

End of year	Alternative V	Alternative W
0 (initial cost)	–\$8000	–\$9000
1–5 (net revenues)	4000	3000
5 (salvage value)	0	8000
Undiscounted payback	2 years	3 years
PW at 10%	\$7163	\$7339

Alternative V has the shorter payback period, but Alternative W has the larger PW.

Payback is a useful measure to the extent that it provides some indication of how long it might take before the initial investment is recovered. It is a helpful *supplementary* measure of the attractiveness of an investment, but it should never be used as the sole measure of quality.

Return on Investment

There are a number of approaches, widely used in industry, that use accounting data (income and expenses) rather than cash flows to determine rate of return, where income and expense are reflected in the firm's accounting statements. Although there is no universally accepted terminology, this accounting-based approach is generally known as *return on investment* (*ROI*), whereas the cash flow approach results in internal rate of return (IRR or RoR).

One formulation of the ROI is the ratio of the average annual accounting profit to the *original book value* of the asset. Another variation is the ratio of the average annual accounting profit to the *average book value* of the asset over its service life. In any event, such computations are based on depreciation expense, an accounting item which is not a cash flow and which is affected by relevant tax regulations. (See the following section, Depreciation.) Therefore, the use of ROI is not recommended as an appropriate figure of merit.

Unequal Service Lives

One of the fundamental principles of capital allocation, is that alternative investment proposals must be evaluated over a common planning horizon. Unequal service lives among competing feasible alternatives complicate this analysis. For example, consider two alternatives: one has life of N_1, the other has life of N_2, and $N_1 < N_2$.

Repeatability (Identical Replication) Assumption. One approach, widely used in engineering economy textbooks, is to assume that (1) each alternative will be replaced at the end of its service life by an identical replacement, that is, the amounts and timing of all cash flows in the first and all succeeding replacements will be identical to the initial alternative; and (2) the planning horizon is at least as long as the common multiple of the lives of the alternatives.

Under these assumptions, the planning horizon is the least common multiple of N_1 and N_2. The *annual worth* method may be used directly since the AW for alternative 1 over N_1 periods is the same as the AW for alternative 1 over the planning horizon.

Specified Planning Horizon. Although commonly used in the literature of engineering economy, the repeatability assumption is rarely appropriate in real-world applications. In such cases, it is generally more reasonable to define the planning horizon N on some basis other than the service lives of the competing alternatives. Equipment under consideration may be related to a certain product, for example, which will be manufactured over a specified time period.

If the planning horizon is *longer* than the service life of one or more of the alternatives, it will be necessary to estimate the cash flow consequences, if any, during the interval(s) between the service life (or lives) and the end of the planning horizon. If the planning horizon is *shorter* than the service lives of one or more of the alternatives, all cash flows beyond the end of the planning horizon are irrelevant. In the latter case, it will be necessary to estimate the salvage value of the "truncated" proposal at the end of the planning horizon.

AFTER-TAX ECONOMY STUDIES

Most individuals and business firms are directly influenced by taxation. Cash flows resulting from taxes paid (or avoided) must be included in evaluation models, along with cash flows from investment, maintenance, operations, and so on. Thus decision makers have a clear interest in cash flows for taxes and related topics.

Depreciation

There is a good deal of misunderstanding about the precise meaning of *depreciation.* In economic analysis, depreciation is *not* a measure of the loss in market value or equipment, land, buildings, and the like. It is *not* a measure of reduced serviceability. Depreciation is strictly an *accounting* concept. Perhaps the best definition is provided by the Committee on Terminology of the American Institute of Certified Public Accountants:

> Depreciation accounting is a system of accounting which aims to distribute the cost or other basic value of tangible capital assets, less salvage (if any), over the estimated life of the unit (which may be a group of assets) in a systematic and rational manner. It is a process of allocation, not of valuation. Depreciation for the year is the portion of the total charge under such a system that is allocated to the year.*

Depreciable property may be tangible or intangible. *Tangible* property is any property that can be seen or touched. *Intangible* property is any other property—for example, a copyright or franchise.

Depreciable property may be real or personal. *Real* property is land and generally anything erected on, growing on, or attached to the land. *Personal* property is any other property, for example, machinery or equipment. (*Note:* Land is never depreciable because it has no determinable life.)

To be depreciable, property must meet three requirements: (1) it must be used in business or held for the production of income, (2) it must have a determinable life longer than 1 year, and (3) it must be something that wears out, decays, gets used up, becomes obsolete, or loses value from natural causes. Depreciation begins when the property is placed in service; it ends when the property is removed from service.

For the purpose of computing taxable income on income tax returns, the rules for computing allowable depreciation are governed by the relevant taxing authority. An excellent reference on federal income taxes is *How to Depreciate Property, Publication 946,* published by the Internal Revenue Service (IRS), U.S. Department of the Treasury. Publication 946 is updated annually.†

A variety of depreciation methods have been and are currently permitted by taxing authorities in the United States and other countries. The discussion that follows is limited to the three methods that are of most interest at the present time. The straight line and declining balance methods are used mainly outside the United States. The Modified Accelerated Cost Recovery System (MACRS) is used currently by the federal government as well as by most states in the United States. Moreover, as will be shown, the straight line and declining balance methods are embedded within the MACRS method, and it is for this reason that the straight line (SL) and declining balance (DB) methods are included here.

1. *Straight line method.* In general, the allowable depreciation in tax year j, D_j, is given by

$$D_j = \frac{B - S}{N} \text{ for } j = 1, \ldots, N \tag{3.1.25}$$

where B is the adjusted cost basis, S is the estimated salvage value, and N is the depreciable life.

Allowable depreciation must be prorated on the basis of the period of service for the tax year in which the property is placed in service and the year in which it is removed from service. For example, suppose that B = \$90,000, N = 6 years, S = \$18,000 after 6 years, and the property is to be placed in service at midyear. In this case,

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*American Institute of Certified Public Accountants, *Accounting Research Bulletin no. 22* (American Institute of Certified Public Accountants, New York, 1944) and American Institute of Certified Public Accountants, *Accounting Terminology Bulletin no. 1* (American Institute of Certified Public Accountants, New York, 1953).

† The discussion of depreciation accounting is necessarily abbreviated in this handbook. The reader is encouraged to consult competent tax professionals and/or relevant publications of the Internal Revenue Service for more thorough treatment of this complex topic.

$$D_j = \frac{\$90{,}000 - \$18{,}000}{6} = \$12{,}000 \qquad \text{for } j = 2, \ldots, 6$$

$$D_1 = D_7 = (6/12)(\$12{,}000) = \$6000$$

The *book value* of the property at any point in time is the initial cost less the accumulated depreciation. In this numerical example, the book value at the start of the third tax year would be \$90,000 – \$6000 – \$12,000 = \$72,000.

2. *Declining balance method.* The amount of depreciation taken each year is subtracted from the book value before the following year's depreciation is computed. A constant *depreciation rate* (*a*) applies to a smaller, or declining, balance each year. In general,

$$D_j = \begin{cases} \pi_1 aB & \text{for } j = 1 \\ aB_j & \text{for } j = 2, 3, \ldots, N+1 \end{cases} \tag{3.1.26}$$

where π_1 = portion of the first tax year in which the property is placed in service

$$(0 < \pi_1 \leq 1)$$

B_j = book value in year j prior to determining the allowable depreciation

Assuming that the property is placed in service at the start of the tax year ($\pi_1 = 1.00$), it may be shown that

$$D_j = Ba(1 - a)^{j-1} \tag{3.1.27}$$

When $a = 2/N$, the depreciation scheme is known as the *double declining balance method,* or simply DDB.

To illustrate using the previous example, suppose that we have DDB with $a = 2/6 = 0.333$. Since $\pi_1 = 6/12 = 0.5$,

$$D_1 = \pi_1 aB = 0.5(0.333)(\$90{,}000) = \$15{,}000$$

$$D_2 = a(B - D_1) = 0.333(\$90{,}000 - \$15{,}000) = \$25{,}000$$

Salvage value is not deducted from the cost or other basis in determining the annual depreciation allowance, but *the asset cannot be depreciated below the expected salvage value.* In other words, once book value equals salvage value, no further depreciation may be claimed.

3. *MACRS (GDS and ADS).* Under the 1986 Tax Reform Act, the Modified Accelerated Cost Recovery System (MACRS, pronounced "makers") is permitted for the purpose of determining taxable income on federal income tax returns. MACRS consists of two systems that determine how qualified property is depreciated. The main system is called the **General Depreciation System** (**GDS**) and the other is called the **Alternative Depreciation System** (**ADS**). MACRS applies to most depreciable property placed in service after December 31, 1986.

a. *Class lives and property classes.* Both GDS and ADS have preestablished class lives for most property. These are summarized in a table of class lives and recovery periods at the back of IRS *Publication 946.* There are eight recovery periods based on these class lives: 3-, 5-, 7-, 10-, 15-, and 20-year properties, as well as two additional real property classes, *nonresidential real* property and *residential rental* property.

b. *Depreciation methods.* There are a number of ways to depreciate property under MACRS, depending on the property class, the way the property is used, and the taxpayer's election to use either GDS or ADS. These are summarized in the following table:

Property class	Primary GDS method	Optional method
3- 5- 7- 10-year (nonfarm)	200% declining balance over GDS recovery period	Straight line over GDS recovery period or 150% DB over ADS recovery period
15- 20-year (nonfarm) *or* property used in farming, except real property	150% declining balance over GDS recovery period	Straight line over GDS recovery period or straight line over ADS recovery period
Nonresidential real and residential rental property	Straight line over GDS recovery period	Straight line over fixed ADS recovery period

Where the declining balance method is used, the switch to the straight line method occurs in the first tax year for which the SL method, when applied to the adjusted basis at the beginning of the year, will yield a larger deduction than had the DB method been continued. Zero salvage value is assumed for the purpose of computing allowable depreciation expense.

The Placed-in-Service Convention. With certain exceptions, MACRS assumes that all property placed in service (or disposed of) during a tax year is placed in service (or disposed of) at the midpoint of that year. This is the *half-year* convention.

Depreciation Percentages. The annual depreciation percentages under GDS, assuming the half-year convention, are summarized in Table 3.1.3. For 3-, 5-, 7-, 10-, 15-, and 20-year properties, the depreciation percentage in year *j* for property class *k* under ADS is given by

TABLE 3.1.3 Annual Depreciation Percentages Under MACRS (Half-Year Convention)

	Recovery period (k)					
Recovery year	3-year	5-year	7-year	10-year	15-year	20-year
1	33.33	20.00	14.29	10.00	5.00	3.750
2	44.45	32.00	24.49	18.00	9.50	7.219
3	14.81	19.20	17.49	14.40	8.55	6.677
4	7.41	11.52	12.49	11.52	7.70	6.177
5		11.52	8.93	9.22	6.93	5.713
6		5.76	8.92	7.37	6.23	5.285
7			8.93	6.55	5.90	4.888
8			4.46	6.55	5.90	4.522
9				6.56	5.91	4.462
10				6.55	5.90	4.461
11				3.28	5.91	4.462
12					5.90	4.461
13					5.91	4.462
14					5.90	4.461
15					5.91	4.462
16					2.95	4.461
17						4.462
18						4.461
19						4.462
20						4.461
21						2.231

$$p_j = \begin{cases} 0.5/k, & j = 1 \\ 1.0/k, & j = 2,3, \dots ,k \\ 0.5/k, & j = k + 1 \end{cases} \tag{3.1.28}$$

Other Deductions from Taxable Income

In addition to depreciation, there are several other ways in which the cost of certain assets may be recovered over time.

Amortization. Amortization permits the taxpayer to recover certain capital expenditures in a way that is like straight line depreciation. Qualifying expenditures include certain costs incurred in setting up a business (for example, survey of potential markets, analysis of available facilities), the cost of a certified pollution control facility, bond premiums, and the costs of trademarks and trade names. Expenditures are amortized on a straight-line basis over a 60-month period or more.

Depletion. Depletion is similar to depreciation and amortization. It is a deduction from taxable income applicable to a mineral property, an oil, gas, or geothermal well, or standing timber. There are two ways to figure depletion: cost depletion and percentage depletion. With certain restrictions, the taxpayer may choose either method.

Section 179 Expense. The taxpayer may elect to treat the cost of certain qualifying property as an expense rather than as a capital expenditure in the year the property is placed in service. *Qualifying property* is "Section 38 property"—generally, property used in the trade or business with a useful life of three years or more for which depreciation or amortization is allowable, with certain limitations, and that is purchased for use in the active conduct of the trade or business.

The total cost that may be deducted for a tax year may not exceed some maximum amount M*. The expense deduction is further limited by the taxpayer's total investment during the year in Section 179 property: The maximum M is reduced by $1 for each dollar of cost in excess of $200,000. That is, no Section 179 expense deduction may be used if total investment in Section 179 property during the tax year exceeds $200,000 + M. Moreover, the total cost that may be deducted is also limited to the taxable income that is from the active conduct of any trade or business of the taxpayer during the tax year. See IRS Publication 946 for more information.

The cost basis of the property must be reduced by the amount of the Section 179 expense deduction, if any, before the allowable depreciation expense is determined.

Gains and Losses on Disposal of Depreciable Assets

The value of an asset on disposal is rarely equal to its book value at the time of sale or other disposition. When this inequality occurs, a gain or loss on disposal is established. In general, the *gain* on disposition of depreciable property is the net salvage value minus the adjusted basis of the property (its book value) at the time of disposal. The *adjusted basis* is the original cost basis less any accumulated depreciation, amortization, Section 179 expense deduction, and where appropriate, any basis adjustments due to the investment credit claimed on the property. A negative gain is considered a *loss* on disposal.

All gains and losses on disposal are treated as *ordinary* gains or losses, *capital* gains or losses, or some combination of the two. The rules for determining these amounts are too complex to be discussed adequately here; interested readers should therefore consult a competent expert and/or read the appropriate sections in *Tax Guide for Small Business* (IRS Publication 334) or a similar reference.

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* M = $18,500 in 1998, $19,000 in 1999, $20,000 in 2000, $24,000 in 2001 and 2002, and $25,000 after 2002.

Federal Income Tax Rates for Corporations

Income tax rates for corporations are adjusted from time to time, largely in order to affect the level of economic activity. The current *marginal* federal income tax rate for corporations is detailed in the following table.

If the taxable income is:

At least	But not more than	Marginal tax rate is
\$0	\$50,000	0.15
\$50,000	\$75,000	0.25
\$75,000	\$100,000	0.34
\$100,000	\$335,000	0.39
\$335,000	\$10 million	0.34
\$10 million	\$15 million	0.35
\$15 million	\$18.33 million	0.38
\$18.33 million	and over	0.35

It may be shown that the *average* tax rate is 35 percent if the total taxable income is at least \$18.33 million.

When income is taxed by more than one jurisdiction, the appropriate tax rate for economy studies is a combination of the rates imposed by the jurisdictions. If these rates are independent, they may simply be added. But the combinatorial rule is not quite so simple when there is interdependence. Income taxes paid to local and state governments, for example, are deductible from taxable income on federal income tax returns, but the reverse is not true: Federal income taxes are not deductible from local returns. Thus, considering only state (t_s) and federal (t_f) income tax rates, the combined incremental tax rate (t) for economy studies is given by

$$t = t_s + t_f(1 - t_s) \tag{3.1.29}$$

Timing of Cash Flows for Income Taxes

The equivalent present value of tax consequences requires estimates of the *timing* of cash flows for taxes. A variety of operating conditions affect the timing of income tax payments. It is neither feasible nor desirable to catalog all such conditions here. In most cases, however, the following assumptions will serve as a reasonable approximation.

1. Income taxes are paid quarterly at the end of each quarter of the tax year.
2. Ninety percent of the firm's income tax liability is paid in the tax year in which the expense occurs; the remaining 10 percent is paid in the first quarter of the following tax year.
3. The four quarterly tax payments during the tax year are uniform.

The timing of these cash flows can be approximated by a weighted average of quarter-ending dates:

$$0.225(\tfrac{1}{4} + \tfrac{2}{4} + \tfrac{3}{4} + \tfrac{4}{4}) + 0.1(\tfrac{5}{4}) = 0.6875$$

That is, the cash flow for income taxes in a given tax year can be assumed to be concentrated at a point 0.6875 into the tax year. (An alternative approach is to assume that cash flows for income taxes occur at the end of the tax year.)

After-Tax Analysis

The following procedures are followed to prepare an after-tax analysis.

1. Specify the assumptions and principal parameter values, including
   - Tax rates (federal and other taxing jurisdictions, as appropriate).
   - Relevant methods related to depreciation, amortization, depletion, investment tax credit, and Section 179 expense deduction.
   - Length of planning horizon.
   - Minimum attractive rate return—the interest rate to be used for discounting cash flows. *Caution:* This rate should represent the *after-tax* opportunity cost to the taxpayer; it will almost always be lower than the pretax MARR. The same discounting rate should *not* be used for both before-tax and after-tax analyses.
2. Estimate the amounts and timing of cash flows other than income taxes. It will be useful to separate these cash flows into three categories:
   - Cash flows that have a *direct* effect on taxable income, as either income or expense. Examples include sales receipts, direct labor savings, material costs, property taxes, interest payments, and state and local income taxes (on federal returns).
   - Cash flows that have an *indirect* effect on taxable income through depreciation, amortization, depletion, Section 179 expense deduction, and gain or loss on disposal. Examples include initial cost of depreciable property and salvage value.
   - Cash flows that do not affect taxable income. Examples include working capital and the portion of loan repayments that represents payment of principal.
3. Determine the amounts and timing of cash flows for income taxes.
4. Find the equivalent present value of cash flows for income taxes at the *beginning of the first tax year.* To that end, let P_j denote the equivalent value of the cash flow for taxes in year j, as measured at the start of tax year j.

$$P_j \simeq T_j\,(1+i)^{-0.6875} \qquad j = 1,2,\ldots,N+1 \tag{3.1.30}$$

where i is the effective annual discount rate and N is the number of years in the planning horizon.

The equivalent present value of all the cash flows for taxes, as measured at the start of the first tax year, is given by

$$P(T) = \sum_{j=1}^{N+1} P_j(1+i)^{-j+1} = \sum_{j=1}^{N+1} T_j(1+i)^{0.3125-j} \tag{3.1.31}$$

5. Find the equivalent present value of the cash flows for taxes, where *present* is defined as the start of the planning horizon. For example, if the property is placed in service at the end of the third month of the tax year, the present value adjustment is $P(T) \times (1+i)^{3/12}$.
6. Find the equivalent present value of all other cash flows estimated in step 2. Use the after-tax MARR. Here the present is defined as the start of the planning horizon.
7. Combine steps (5) and (6) to yield the total net present value (NPV), or present worth (PW).

Note: If it is desired to determine the *after-tax rate of return* rather than PW (or FW, EUAC, and so on), steps 4 to 7 must be modified. With the appropriate present worth equation for all cash flows, set the equation equal to zero and find the value of the interest rate i^* such that PW = 0. This is the after-tax IRR for the proposed investment.

Numerical Example. Consider the possible acquisition of certain manufacturing equipment with *initial* cost of $400,000. The equipment is expected to be kept in service for 6 years and then sold for an estimated $40,000 *salvage value. Working capital* of $50,000 will be required at the start of the 6-year period; the working capital will be recovered intact at the end of 6 years. If acquired, this equipment is expected to result in *savings* of $100,000 each year. The timing of these savings is such that the continuous cash flow assumption will be adopted throughout each year. The firm's after-tax MARR is 10 percent per year. The *present worth* of these cash flows, *other than income taxes,* is

$$\begin{aligned}\text{PW} &= -\$400{,}000 + \$40{,}000(P/F,\ 10\%, 6)\\ &\quad -\$50{,}000 + \$50{,}000(P/F,\ 10\%, 6)\\ &\quad +\$100{,}000(P/\overline{A},\ 10\%\ 6)\\ &= \$57{,}800\end{aligned}$$

Assume that there is no Section 179 expense deduction. The equipment will be placed in service at the middle of the tax year and depreciated under MACRS as a 5-year recovery property using the half-year convention. The incremental federal income tax rate is 0.35; there are no other relevant income taxes affected by this proposed investment. The PW of the effects of cash flows due to income taxes is summarized in Table 3.1.4. The total PW for this proposed project is as follows:

Cash flows other than income taxes	\$57,759
Effect on cash flows due to income taxes	–16,566
Net present worth	\$41,193

Spreadsheet Analyses. A wide variety of computer programs are available for before-tax and/or after-tax analyses of investment programs. (Relevant computer software is discussed from time to time in the journal, *The Engineering Economist.*) In addition, any of several spreadsheet programs currently available may be readily adapted to economic analyses, usually with very little additional programming. For example, Lotus and Excel include financial functions to find the present and future values of a single payment and a uniform series (annuity), as well as to find the IRR of a series of cash flows. Tables 3.1.4 and 3.1.5 are illustrations of computer-generated spreadsheets.

INCORPORATING PRICE LEVEL CHANGES INTO THE ANALYSIS

The effects of price level changes can be significant to the analysis. Cash flows, proxy measures of goods and services received and expended, are affected by both the *quantities* of goods and services as well as their *prices.* Thus, to the extent that changes in price levels affect cash flows, these changes must be incorporated into the analysis.

The *consumer price index* (CPI) is but one of a large number of indexes that are regularly used to monitor and report for specific economic analyses. Analysts should be interested in *relative price changes of goods and service that are germane to the particular investment alternatives under consideration.* The appropriate indexes are those that are related, say, to construction materials, costs of certain labor skills, energy, and other cost and revenue factors.

General Concepts and Notation

Let p_1 and p_2 represent the prices of a certain good or service at two points in time t_1 and t_2, and let $n = t_2 - t_1$. The relative rate of price changes between t_1 and t_2, the average per period, is given by

$$\text{g} = \sqrt[n]{p_2/p_1} - 1 \tag{3.1.32}$$

We have *inflation* when g > 0 and *disinflation* when g < 0.

Let A_j = cash flow resulting from the exchange of certain goods or services, at end of period

TABLE 3.1.4 Cash Flows for Income Taxes—Numerical Example

Tax year j	Depreciation rate $p_j(5)$	Depreciation D_j	Gain G_N	Other revenue R_j	Taxable income $R_j - D_j + G_N$	Income taxes T_j	PW factor $(1.10)^{0.3125-j}$	PW@10% p_j
1	0.200	\$80,000		\$40,000	\$(40,000)	\$(14,000)	0.93657	\$(13,112)
2	0.3200	128,000		80,000	(48,000)	(16,800)	0.85143	(14,304)
3	0.1920	76,800		80,000	3,200	1,120	0.77403	867
4	0.1152	46,080		80,000	33,920	11,872	0.70366	8,354
5	0.1152	46,080		80,000	33,920	11,872	0.63969	7,594
6	0.0576	23,040		80,000	56,960	19,936	0.58154	11,594
7	0.0000	—	\$40,000	40,000	80,000	28,000	0.52867	14,803
PW measured at start of 1st tax year								\$15,796
Adjustment factor (½ year)								$\times (1.10)^{0.5}$
PW measured at start of planning horizon								\$16,566

Note: Tax rate = 0.35, cost basis = \$400,000.

j, stated in terms of *constant* dollars. (Analogous terms are *now* or *real* dollars.) Let A_j^* = cash flows for those same goods or services in *actual* dollars. (Analogous terms are *then* or *current* dollars.) Then

$$A_j^* = A_j\,(1+g)^j \tag{3.1.33}$$

where g is the periodic rate of increase or decrease in relative price (the *inflation rate*).

As before, let i = the MARR in the absence of inflation, that is, the real MARR. Let i^* = the MARR required taking into consideration inflation, that is, the *nominal* MARR. The periodic rate of increase or decrease in the MARR due to inflation f is given by

$$f = \left(\frac{1+i^*}{1+i}\right) - 1 = \frac{i^* - 1}{1+i} \tag{3.1.34}$$

Other relationships of interest are

$$i^* = (1+i)(1+f) - 1 = i + f + if \tag{3.1.35}$$

and

$$i = \left(\frac{1+i^*}{1+f}\right) - 1 = \frac{i^* - f}{1+f} \tag{3.1.36}$$

T Spreadsheet Analysis—Numerical Example

Project year j	Investment and salvage value	Working capital	Savings during year j	PW of discrete cash flows	PW of continuous cash flows	Total present value
0	(\$400,000)	(\$50,000)		(\$450,000)		(\$450,000)
1			\$100,000		\$95,382	\$95,382
2			\$100,000		\$86,711	\$86,711
3			\$100,000		\$78,828	\$78,828
4			\$100,000		\$71,662	\$71,662
5			\$100,000		\$65,147	\$65,147
6	\$40,000	\$50,000	\$100,000	\$50,803	\$59,225	\$110,028
Total	(\$360,000)	\$0	\$600,000	(\$399,197)	\$456,957	\$57,759
Present worth (NPV) of cash flows for taxes						(\$16,566)
Net present worth						\$41,193

Note: MARR = 10%.

Models for Analysis

It may be shown that the *future worth* of a series of cash flows A_j^* ($j = 1, 2, \ldots, N$) is given by

$$FW = (1 + i^*)^N \sum_{j=0}^{N} A_j(1 + d)^{-j} \tag{3.1.37}$$

where

$$d = \frac{(1 + i)(1 + f)}{1 + g} - 1 \tag{3.1.38}$$

and i, f, and g are as defined previously. From Eq. (3.1.37) it follows that the *present worth* is given by

$$\text{PW} = \sum_{j=0}^{N} A_j(1 + d)^{-j} \tag{3.1.39}$$

Note: In these models it is assumed that both the cash flows and the MARR are affected by inflation, the former by g and the latter by f, and $f \neq g$. If it is assumed that both i and A_j's are affected by the same rate, that is, $f = g$, then Eq. (3.1.39) reduces to

$$PW = \sum_{j=0}^{N} A_j(1 + i)^{-j} \tag{3.1.40}$$

which is the same as the PW model ignoring inflation.

To illustrate, consider cash flows in constant dollars (A_j) of $80,000 at the end of each year for 8 years. The inflation rate for the cash flows (g) is 6 percent per year, the nominal MARR (i^*) is 9 percent per year, and the inflationary effect on the MARR (f) is 4.6 percent per year. Then

$$d = \frac{1 + i^*}{1 + g} - 1 = \frac{1.09}{1.06} - 1 = 0.0283$$

and

$$PW = \sum_{j=1}^{8} A_j(1 + d)^{-j} = \$80{,}000\ (P/A, 2.83\%, 8) = \$565{,}000$$

Multiple Factors Affected Differently by Inflation

In the preceding section it is assumed that the project consists of a single price component affected by rate g per period. But most investments consist of a variety of components, among which rates of price changes may be expected to differ significantly. For example, the price of the *labor* component may be expected to increase at the rate of 7 percent per year, and the price of the *materials* component is expected to decrease at the rate of 5 percent per year. The appropriate analysis in such cases is an extension of Eqs. (3.1.37) through (3.1.39).

Consider a project consisting of two factors, and let A_{j1} and A_{j2} represent the cash flows associated with each of these factors. Let g_1 and g_2 represent the relevant inflation rates, so that

$$A_j^* = A_{j1}(1 + g_1)^j + A_{j2}(1 + g_2)^j \tag{3.1.41}$$

It follows that

$$FW = (1 + i^*)^N \left\{ \left[\sum_{j=1}^{N} A_{j1}(1 + d_1)^{-j} \right] + \left[\sum_{j=1}^{N} A_{j2}(1 + d_2)^{-j} \right] \right\} \tag{3.1.42}$$

and

$$PW = \left\{ \left[\sum_{j=1}^{N} A_{j1}(1 + d_1)^{-j} \right] + \left[\sum_{j=1}^{N} A_{j2}(1 + d_2)^{-j} \right] \right\} \tag{3.1.43}$$

where

$$d_1 = (1 + i^*)/(1 + g_1) \quad \text{and} \quad d_2 = (1 + i^*)/(1 + g_2) \tag{3.1.44}$$

Interpretation of IRR under Inflation

If *constant* dollars (A_j) are used to determine the internal rate of return, then the *inflation-free IRR* is that value of ρ such that

$$\sum_{j=0}^{N} A_j(1 + \rho)^{-j} = 0 \tag{3.1.45}$$

The project is acceptable if $\rho > i$, where i is the inflation-free MARR as in the preceding section.

If *actual* dollars (A_j^*) are used to determine the internal rate of return, then the *inflation-adjusted IRR* is that value of ρ* such that

$$\sum_{j=0}^{N} A_j^*(1 + \rho^*) = 0 \tag{3.1.46}$$

To illustrate, consider a project that requires an initial investment of \$100,000 and for which a salvage value of \$20,000 is expected after 5 years. If accepted, this project will result in annual savings of \$30,000 at the end of each year over the 5-year period. All cash flow estimates are based on constant dollars. If may be shown that, based on these assumptions, $\rho \simeq 19$ percent.

It is assumed that the cash flows for this proposal will be affected by an inflation rate (g) of 10 percent per year. Thus $A_j^* = A_j\,(1.10)^j$, and from Eq. (45), $\rho^* \simeq 31$ percent.

The investor's inflation-free MARR (i) is assumed to be 25 percent. If it is assumed that the MARR is affected by an inflation rate (g) of 10 percent per year, then $i^* = 1.10(1.25) - 1 = 0.375$.

Each of the two comparisons indicates that the proposed project is not acceptable: ρ (19%) < i (25%) and ρ* (31%) < i^* (37.5%).

TREATING RISK AND UNCERTAINTY IN THE ANALYSIS

It is imperative that the analyst recognize the uncertainty inherent in *all* economy studies. The past is irrelevant, except when it helps predict the future. Only the future is relevant, and *the future is inherently uncertain.*

At this point it will be useful to distinguish between *risk* and *uncertainty,* two terms widely used when dealing with the noncertain future. *Risk* refers to situations in which a probability distribution underlies future events and the characteristics of this distribution are known or can be estimated. Decisions involving *uncertainty* occur when nothing is known or can be assumed about the relative likelihood, or probability, of future events. Uncertainty situations may arise when the relative attractiveness of various alternatives is a function of the outcome of pending labor negotiations or local elections, or when permit applications are being considered by a government planning commission.

A wide spectrum of analytical procedures is available for the formal consideration of risk and uncertainty in analyses. Space does not permit a comprehensive review of all these procedures. The reader is referred to any of the general references included in suggestions for further reading for a discussion of one or more of the following:

- Sensitivity analysis
- Risk analysis
- Decision theory applications
- Digital computer (Monte Carlo) simulation
- Decision trees

Some of these procedures can be found elsewhere in this handbook. Other procedures widely used in industry include:

- *Increasing the minimum attractive rate of return.* Some analysts advocate adjusting the minimum attractive rate of return to compensate for risky investments, suggesting that since some investments will not turn out as well as expected they will be compensated for by an incremental "safety margin," Δi. This approach, however, fails to come to grips with the risk or uncertainty associated with estimates for specific alternatives, and thus an element Δi in the minimum attractive rate of return penalizes all alternatives equally.
- *Differentiating rates of return by risk class.* Rather than building a safety margin into a single minimum attractive rate of return, some firms establish several risk classes with separate standards for each class. For example, a firm may require low-risk investments to yield at least 15 percent and medium-risk investments to yield at least 20 percent, and it may define a minimum attractive rate of return of 25 percent for high-risk proposals. The analyst then judges to which class a specific proposal belongs, and the relevant minimum attractive rate of return is used in the analysis.

Although this approach is a step away from treating all alternatives equally, it is less than satisfactory because it fails to focus attention on the uncertainty associated with the individual proposals. No two proposals have precisely the same degree of risk, and grouping alternatives by class obscures this point. Moreover, the attention of the decision maker should be directed to the causes of uncertainty, that is, to the individual estimates.

- *Decreasing the expected project life.* Still another measure frequently employed to compensate for uncertainty is to decrease the expected project life. It is argued that estimates become less and less reliable as they occur further and further into the future; thus shortening project life is equivalent to ignoring those distant, unreliable estimates. Furthermore, distant consequences are more likely to be favorable than unfavorable: Distant estimated cash flows are generally positive (resulting from net revenues) and estimated cash flows near date zero are more likely to be negative (resulting from start-up costs). Reducing expected project life, however, has the effect of penalizing the proposal by precluding possible future benefits, thereby allowing for risk in much the same way that increasing the minimum attractive rate of return penalizes marginally attractive proposals. Again, this procedure is to be criticized on the basis that it obscures uncertain estimates.

ABLES

Table 3.1.6 presents compound interest tables for the single payment, the uniform series, and the gradient series.

FURTHER READINGS

Books (Published 1990 to 1998)

Au, Tung, and Thomas P. Au, *Engineering Economics for Capital Investment Analysis,* Allyn and Bacon, Boston, 1991.

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Clark, F.D., and A.B. Lorenzoni, *Applied Cost Engineering,* 3rd ed., Dekker, New York, 1996.

DeGarmo, E., W.G. Sullivan, James A. Bontadelli, and E.M. Wicks, *Engineering Economy,* 10th ed., Macmillan, New York, 1996.

TABLE 3.1.6 Compound Interest Tables (10 Percent)

	Single payment			Uniform series				Uniform series		Gradient series		
	Compound amount	Present worth		Compound amount		Present worth		Sinking fund	Capital recovery	Uniform series	Present worth	
N	F/P	P/F	$P/\overline{F}$	F/A	$F/\overline{A}$	P/A	$P/\overline{A}$	A/F	A/P	A/G	P/G	N
1	1.100	0.9091	0.9538	1.000	1.049	0.909	0.954	1.0000	1.1000	0.000	0.000	1
2	1.210	0.8264	0.8671	2.100	2.203	1.736	1.821	0.4762	0.5762	0.476	0.826	2
3	1.331	0.7513	0.7883	3.310	3.473	2.487	2.609	0.3021	0.4021	0.937	2.329	3
4	1.464	0.6830	0.7166	4.641	4.869	3.170	3.326	0.2155	0.3155	1.381	4.378	4
5	1.611	0.6209	0.6515	6.105	6.406	3.791	3.977	0.1638	0.2638	1.810	6.862	5
6	1.772	0.5645	0.5922	7.716	8.095	4.355	4.570	0.1296	0.2296	2.224	9.684	6
7	1.949	0.5132	0.5384	9.487	9.954	4.868	5.108	0.1054	0.2054	2.622	12.763	7
8	2.144	0.4665	0.4895	11.436	11.999	5.335	5.597	0.0874	0.1874	3.004	16.029	8
9	2.358	0.4241	0.4450	13.579	14.248	5.759	6.042	0.0736	0.1736	3.372	19.421	9
10	2.594	0.3855	0.4045	15.937	16.722	6.145	6.447	0.0627	0.1627	3.725	22.891	10
11	2.853	0.3505	0.3677	18.531	19.443	6.495	6.815	0.0540	0.1540	4.064	26.396	11
12	3.138	0.3186	0.3343	21.384	22.437	6.814	7.149	0.0468	0.1468	4.388	29.901	12
13	3.452	0.2897	0.3039	24.523	25.729	7.103	7.453	0.0408	0.1408	4.699	33.377	13
14	3.797	0.2633	0.2763	27.975	29.352	7.367	7.729	0.0357	0.1357	4.996	36.801	14
15	4.177	0.2394	0.2512	31.772	33.336	7.606	7.980	0.0315	0.1315	5.279	40.152	15
16	4.595	0.2176	0.2283	35.950	37.719	7.824	8.209	0.0278	0.1278	5.549	43.416	16
17	5.054	0.1978	0.2076	40.545	42.540	8.022	8.416	0.0247	0.1247	5.807	46.582	17
18	5.560	0.1799	0.1887	45.599	47.843	8.201	8.605	0.0219	0.1219	6.053	49.640	18
19	6.116	0.1635	0.1716	51.159	53.676	8.365	8.777	0.0195	0.1195	6.286	52.583	19
20	6.728	0.1486	0.1560	57.275	60.093	8.514	8.932	0.0175	0.1175	6.508	55.407	20

21	7.400	0.1351			67.152	8.649	9.074	0.0156	0.1156	6.719	58.110	21
22	8.140	0.1228			74.916	8.772	9.203	0.0140	0.1140	6.919	60.689	22
23	8.954	0.1117			83.457	8.883	9.320	0.0126	0.1126	7.108	63.146	23
24	9.850	0.1015	0.1065	88.497	92.852	8.985	9.427	0.0113	0.1113	7.288	65.481	24
25	10.835	0.0923	0.0968	98.347	103.186	9.077	9.524	0.0102	0.1102	7.458	67.696	25
26	11.918	0.0839	0.0880	109.182	114.554	9.161	9.612	0.0092	0.1092	7.619	69.794	26
27	13.110	0.0763	0.0800	121.100	127.059	9.237	9.692	0.0083	0.1083	7.770	71.777	27
28	14.421	0.0693	0.0728	134.210	140.814	9.307	9.765	0.0075	0.1075	7.914	73.650	28
29	15.863	0.0630	0.0661	148.631	155.945	9.370	9.831	0.0067	0.1067	8.049	75.415	29
30	17.449	0.0573	0.0601	164.494	172.588	9.427	9.891	0.0061	0.1061	8.176	77.077	30
31	19.194	0.0521	0.0547	181.944	190.896	9.479	9.945	0.0055	0.1055	8.296	78.640	31
32	21.114	0.0474	0.0497	201.138	211.035	9.526	9.995	0.0050	0.1050	8.409	80.108	32
33	23.225	0.0431	0.0452	222.252	233.188	9.569	10.040	0.0045	0.1045	8.515	81.486	33
34	25.548	0.0391	0.0411	245.477	257.556	9.609	10.081	0.0041	0.1041	8.615	82.777	34
35	28.102	0.0356	0.0373	271.025	284.361	9.644	10.119	0.0037	0.1037	8.709	83.987	35
40	45.259	0.0221	0.0232	442.593	464.371	9.779	10.260	0.0023	0.1023	9.096	88.953	40
45	72.891	0.0137	0.0144	718.906	754.280	9.863	10.348	0.0014	0.1014	9.374	92.454	45
50	117.391	0.0085	0.0089	1,163.910	1,221.181	9.915	10.403	0.0009	0.1009	9.570	94.889	50
55	189.059	0.0053	0.0055	1,880.594	1,973.130	9.947	10.437	0.0005	0.1005	9.708	96.562	55
60	304.482	0.0033	0.0034	3,034.821	3,184.151	9.967	10.458	0.0003	0.1003	9.802	97.701	60
65	490.372	0.0020	0.0021	4,893.715	5,134.514	9.980	10.471	0.0002	0.1002	9.867	98.471	65
70	789.748	0.0013	0.0013	7,887.483	8,275.592	9.987	10.479	0.0001	0.1001	9.911	98.987	70
80	2,048.405	0.0005	0.0005	20,474.045	21,481.484	9.995	10.487	0.0000	0.1000	9.961	99.561	80
90	5,313.035	0.0002	0.0002	53,120.348	55,734.168	9.998	10.490	0.0000	0.1000	9.983	99.812	90

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BIOGRAPHY

G.A. Fleischer received his B.S. degree from St. Louis University, his M.S. degree from the University of California (Berkeley), and his Ph.D. degree in industrial engineering and engineering-economic planning from Stanford University. He is the author or coauthor of more than 100 refereed professional publications and 5 textbooks. Joining the faculty of the Department of Industrial and Systems Engineering at the University of Southern California in 1964, Dr. Fleischer is currently Professor Emeritus. Academic and professional honors include election to the grade of fellow of the Institute of Industrial Engineers and selection for the Wellington Award for exceptional contributions to the theory and practice of engineering economy.

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CHAPTER 3.2

BUDGETING AND PLANNING FOR PROFITS

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This chapter will show how to maximize the rate of return on equity capital through a well-constructed corporate profit plan. The industrial engineer will find a straightforward discussion on how to establish a plan, what items should be included in the profit planning, and the importance of ongoing comparison of actual results versus those on the model. Examples will show how any company can improve its returns by determining costs, sales, and marginal incomes; how to calculate these projections; and then establish profit targets through a well-detailed five-step process. Finally, the industrial engineer is given instructions on how to use comparative data to make operational choices that will provide the maximum possible benefit to the company's profitability and how to overcome objections from those who may not see the direct relevance of planning to profits.

BACKGROUND

Profits Don't Just Happen

Profits don't just happen. They must be *planned.* The development of realistic plans for the company and for each of its major divisions and product lines is an essential function of management. The continuing comparison of actual operating results with the plan is one of the most important means of control available to management.

The Object of Profit Planning

The *object* of profit planning is to make the most effective use of resources and thereby obtain the highest level of sustained profits. In almost every major industry there are companies with relatively modest resources that are making profits equal to or greater than those of competitors with far more capital. Most of the time, the reason is that the more successful company is doing a better job of planning. It is using a carefully coordinated system to chart the course it means to follow.

Use of Projections

To construct a preliminary plan, the planner's first estimate of profitability is in the period for which the plan applies, the planner uses two sets of projections, one related to the profit and loss statement, the other to the balance sheet.

Projections keyed to the company's profit and loss statement include

- Sales for each division, product, or product line.
- Variable manufacturing costs attributable to each.
- Variable costs of marketing and distribution attributable to each.
- The difference between the selling price and the total variable costs of manufacturing and marketing. This is the marginal income attributable to each unit or product.
- Period costs (common and distributed).

Projections keyed to the balance sheet include

- Accounts receivable
- Property, plant, and equipment
- Inventories of raw materials and of finished goods
- Investment in research and development
- Investment in patents and other proprietary items

Drafting the Preliminary Plan

Using these basic tools, the planner drafts a preliminary plan showing the established performances of each unit or product and the total profits this will generate for the company. The planner then constructs a model that compares the preliminary plan with targets for the same business unit or product line estimated on the basis of the rate of return management seeks to get on resources earmarked for that unit or product line. Such a comparison may reveal an opportunity to use ideal capacity, change the product mix, or reduce investment in some lines. It may also show the need to revise the targets to make them conform to realistic forecasts.

The model can be used to answer "what if" questions, showing what would happen to sales, costs, and profits under various assumptions about markets, prices, investment, and product mix. In many ways it is the most powerful tool available to top management for charting the future course of the company. At the same time, it is invaluable to lower levels of management where it can be used to improve profitability or to analyze the effects of a change in design.

The Role of the Industrial Engineer

The industrial engineer should be a key person throughout the planning process. Industrial engineers' understanding of the manufacturing process, the raw material requirements, and the plant and equipment needs in each product line is invaluable in determining realistic targets. Their continuing role in product evaluation puts them constantly in touch with all areas and divisions of the organization.

The industrial engineer should be the primary supplier of the manufacturing inputs and forecasts required in the budgeting and planning process. His or her role is therefore critical in ensuring that the most accurate planning information is available to management.

BUDGETING AND PLANNING FOR PROFITS

CONCEPTS THE PLANNER USES

Common Planning Mistakes Companies Make

The result of planning should be to maximize the ratio of profits to the equity capital employed—that is, the rate of return on the assets that the owners of the business have committed to it. One of the common mistakes that companies make is to concentrate on profit as a percent of sales rather than keeping a steady watch on what the owners are making on their investment.

Table 3.2.1 shows key items from the balance sheets and income statements of two manufacturing companies. Their profits to sales ratios compare as shown in Table 3.2.2.

TABLE 3.2.1 Company Comparison: Company A vs. Company B

($000)	Plan	Revised	Difference	
Balance sheet				
Assets	$110,000	$190,000	$80,000	Greater
Liabilities	45,000	90,000	45,000	Greater
Equity Capital Employed	65,000	100,000	35,000	Greater
Income statement				
Net Plan Sales	$225,000	$270,000	$45,000	Greater
Variable Mfg. Cost of Sales	135,000	135,000	—	No. Diff.
Total Marginal Income	90,000	135,000	45,000	Greater
Period Mfg.	20,000	40,000	20,000	Greater
Cost of Sales	155,000	175,000	20,000	Greater
Period Selling G&A	40,000	55,000	15,000	Greater
Operating Profit Before Tax	30,000	40,000	10,000	Greater
Profit After Tax	15,000	20,000	5,000	Greater
Ratios				
Marginal Income	40.00%	50.00%	10.00%	Greater
ROA Before Tax	27.27%	21.05%	–6.22%	Smaller
Profit to Equity Capital Employed After Tax	23.08%	20.00%	–3.08%	Smaller
Profit to Sales Before Tax	13.33%	14.81%	1.48%	Greater
Margin of Safety	33.00%	29.60%	–3.40%	Smaller
Breakeven	$150,000	$230,000	$80,000	Greater

TABLE 3.2.2 Company Comparison of Profit to Sales (P/S) Ratios: Company A vs. Company B

($000)	Sales	Profits	Profits before taxes as a percent of sales
Company A	$225,000	$30,000	13.33%
Company B	270,000	40,000	14.81%

At first glance, Company B seems to be doing substantially better than its competitor. But take a look at what happens when the analyst refused to stop with the percent of profit and compares the two companies on the basis of the rates of return they earned on the resources used in their businesses (see Table 3.2.3).

TABLE 3.2.3 Comparison of Profit to Equity Capital Employed (ECE): Company A vs. Company B

($000)

	Equity capital employed	Profits	Profits before taxes as a percent of equity capital employed
Company A	$65,000	$30,000	46.15%
Company B	$100,000	$40,000	40.00%

It is apparent that Company A, with a somewhat smaller investment, is making a significantly better return on its assets than Company B. Obviously, Company A's profit planning is making the most out of what it has. Further evidence of this is the pretax return on total assets—27 percent for Company A, which compares with 21 percent for Company B.

The succeeding sections of this chapter outline the steps that Company B can take to upgrade its performance and improve its returns.

The Profit on Equity Capital Employed Ratio

The profits to equity capital employed ratio (P/ECE) is a product of two other ratios: profit to sales (P/S) and sales to equity capital employed (S/ECE). The profit to sales ratio measures the number of cents that the company can keep out of each sales dollar. The sales to equity capital employed ratio measures the number of times equity capital employed turned over in terms of sales dollars. The two ratios multiplied together give the profit on equity capital employed ratio:

$$\mathrm{P/S} \times \mathrm{S/ECE} = \mathrm{P/ECE}$$

Control of the P/S and S/ECE ratios—and through them the P/ECE ratio—is achieved by comparison of actual and target marginal income: the amount of the sales dollar that is left after costs generated by the product process. To estimate marginal income, the planner must forecast sales and identify the two major categories of cost—those that vary with the rates of production and those that are fixed for the period ahead regardless of output levels.

Preparing the Marketing Plan

The planning process begins with the preparation of the marketing plan. An effective marketing plan will answer such questions as

- What products will sell and in what volumes?
- At what prices?
- At what promotional costs?
- When and by what selling method?
- What product mix does this plan require?

But the answers to these questions will be useful only if their impact on profits can be determined. To make such a determination, the planner must turn to marginal income accounting. Because the unit profit contribution for a particular product stays constant in the marginal income approach, it is easy to pinpoint the effect of volume swings. Simple multiplication of the units to be sold by the constant rate of contribution will give the answer in terms of profits.

The Importance of Marginal Income Estimates

Marginal income (MI) estimates provide the benchmarks for making pricing decisions. Knowing how much each product contributes to total marginal income, sales executives can develop a price structure that maximizes the sales of the products that contribute most to company profits. Similarly, when open plant capacity exists, any price obtained above the standard direct cost of an item will generate marginal income to cover period costs and contribute toward profit.

Pricing policies must be reevaluated continually in response to shifts in competition, demand, and supply. The key to successful pricing is rapid and knowledgeable response to these hectic conditions in the actual marketplace. The marginal income approach provides the timely and reliable guidance the marketing executive needs to make a successful response designed to achieve the profit targets. With rapid feedback of information on market conditions and direct cost variances, the marketing executive can readily detect departures from the planned targets and change the pricing and selling effort accordingly.

Marginal income is the most useful of all concepts available to the planner. It is a key that opens the way to reliable, scientific analysis of profit opportunities in spite of the uncertainties and breathtaking changes of the modern business world. Marginal income costing is particularly well suited to computerization because it is specifically designed to deal with variances—real and projected—in volume, prices, various kinds of costs, and capacity utilization. It provides investors with a clear picture of the results of operations.

The vital role of marginal income costing makes precise definitions essential.

Variable Costs. Costs that go up or down in step with production of the product or performance of the service involved are variable costs. They are the specific costs of making or delivering a product or service.

Period Costs. Costs that vary only gradually over time periods, as long as operations remain within normal capacity levels, are period costs. They are considered the costs of being in business and are not susceptible to control at production level. In most cases, variable costs are controlled at the line or production level, while period costs are controlled at the management level.

Marginal Income. This is sales minus variable costs. It can be measured at two levels—manufacturing marginal income, which is the amount left out of the sales dollar after direct costs of production have been subtracted, and marketing marginal income, which is what remains after the direct sales and distribution costs have been paid.

IDENTIFYING VARIABLE COSTS

The Power to Control Costs. In distinguishing between variable and period costs, the planner should not underestimate the power of the company to control its costs. If an expense cannot be clearly identified as period, it should be classified as variable. The decision should be made on the basis of what could be done, not on the assumption that nothing will be done.

Labor. Assuming no major change in productivity, production line labor costs will vary directly with the rate of output. But all payroll costs are by no means variable. Some employees are, in effect, period cost workers, while the majority of line workers are variable cost workers.

Raw Materials. As long as the specifications for the product remain the same, the cost of raw materials can be expected to vary with the rate of production. However, there may be opportunities here to change the specifications or find a new source of supply, thereby reducing the cost at each level of output. Here again the planning process highlights opportunities to increase profitability.

Distribution Costs. Though some marketing costs will be keyed to sales and production, others may depend on management decisions. This is especially true in marketing and distribution where different means of reaching the final consumer are likely to involve strikingly different costs.

Variable Cost Planning as a Tool. Variable cost planning is a precision tool. It is far and away the best method available not only for profit planning but also for the entire cost system of the company. By associating only variable costs with a product, management eliminates the information fog caused by volume variance. Most of the budgeting and standard costs systems of the past were inflexible and useless if output missed the target rate the plan set for it. This happened because in trying to assign whole costs to each product, companies used a device called under- or overabsorbed burden, and this was estimated on the basis of an assumed "normal" rate of operation. But as any plant manager knows, total costs per unit will come out to a predetermined figure only if production hits the assumed level on the dot. If production runs higher, per unit costs will be less than forecast; if it runs lower, they will be greater.

MANAGING PERIOD COSTS

Fixed Versus Period Costs

Accountants used to use the term *fixed costs* as though no change was possible. The modern term, *period costs,* reflects an increasing recognition that these costs are fixed for a specific time frame only. They may be out of management's reach for months, but most of them can be managed over time.

It is true that some costs, such as insurance and depreciation on existing plant, are fixed for the foreseeable future and little can be done to change them. But others, such as heating, air conditioning, and snow plowing are seasonal. Still others, including a number of major staff costs, are determined by previous management decisions.

SETTING THE CRUCIAL RATIOS

Establishing Profit Targets

With the figures on costs, sales, and marginal incomes in hand, the planner can begin to set up profit targets. There are two yardsticks that can be used. One is what has been earned in the past. The other is what could be earned with the most effective possible use of the resources available to management. These two figures establish a minimum and a maximum—a range of profit within which the company's projected performance should fall.

Realistic targets have to be established by careful analysis of projections for key items in the profit/loss statement and the balance sheet. These projections can be divided into any logical organization categories, such as

BUDGETING AND PLANNING FOR PROFITS

- Business units
- Major divisions of the company
- Product groups
- Individual products or product lines

To develop a realistic final profit target, a planning team must go through a five-step process:

1. Develop preliminary projections of sales, variable costs, and marginal income for each planning unit; then estimate how much total profit will remain after period costs have been deducted.
2. Develop projections for the balance sheet items attributable to each unit.
3. Calculate the rate of return that management expects to make on each asset shown by the balance sheet.
4. Develop alternate profit targets for each unit designed to yield the required rate of return and cover direct costs to provide greater profitability for the company in total.
5. Compare the marginal income targets of the preliminary plan with marginal income driven by the rate of return method.

A careful study of differences between the two tentative targets for each unit will show where a change of prices, a shift in product mix, a reduction of costs, or change in product-related assets could increase the profits to equity capital employed ratio (P/ECE) and maximize total profitability of the company. The planners can use the model they have constructed to ask a variety of "what if" questions, assessing the impact of possible changes. In the end they can set up a final group of targets that will come close to the top of the profit range.

The Sales Forecast

Construction of the model begins with the preliminary plan, and construction of the preliminary plan begins with sales forecasts. There are several steps, involving very little labor that will help make a sales target realistic. One is to take account of the growth trend of the company and its industry. Every industry has a rate of growth over a period of years. This growth curve can be found and projected.

Table 3.2.4 shows the results for Company B. This analysis will not only show whether projected sales can be met with existing capacity, but it will also give management a picture of how much capacity is being used and how much is idle.

Management, of course, still has the option of putting more effort into its sales program. If the profits yielded by the final sales volume target are inadequate, it may be possible to adjust the targets to achieve the profit goal. These adjustments may call for expansion of the company itself or changes in its basic structure, for example:

TABLE 3.2.4 Cumulative Product Marginal Income Analysis: Company B

($000)

Product	Sales	MI%	Cummulative MI
Customer special	$80,000	70.00%	$56,000
OEM stock	$70,000	50.00%	$91,000
Customer stock	$85,000	41.20%	$126,000
OEM special	$35,000	25.70%	$135,000

- Additional capacity in certain departments
- Larger sales forces
- Alternations or additions to sales territories
- New products

A sales manager with a $2 million promotion budget can use Table 3.2.4 to work out a strategy. Heavy promotion of a customer special will be tempting because of the 70 percent marginal income, but the broad spread between planned MI and the return on assets (ROA) target MI developed later suggested that a price cut would be smarter. Original equipment manufacturing (OEM) stock with a 50 percent MI has only $4.5 million in unused capacity. The sales manager will scarcely get the promotion costs back before production hits the limit ($4.5 million × 50 percent = $2.25 million). This would give a gain of only $2,250,000 for all the sales manager's efforts. It will make better sense to concentrate on customer stock where there is $20 million potential capacity at 41.2 percent MI, provided there is room for market expansion.

Manufacturing Costs

Once the sales target is set, the planners can establish a target for manufacturing costs. Like the sales forecasts, the manufacturing cost targets should be stated briefly and simply. They should never be designed for use in the detailed variance analysis that effective cost control requires. The planning forecasts should stick to the most significant targets and the broad measures of performance. The purpose of planning is to give the company a basic outline of what it must do to maximize profitability.

In several major categories of cost, however, the planners will have to ask questions that the cost control system should answer. These cost categories include

- Capacity utilization of equipment centers
- Price to be paid for production materials and supplies
- Target allowance for rework and scrap
- Rates to be paid for labor
- Allowance for maintenance

The standard cost system should pick up most of these items on a "should be" or target basis. The industrial engineer is best suited to address this array of attainable targets or standards.

The final manufacturing targets should be expressed in terms of volume and units, using the same categories as the sales forecast. In addition, supplementary targets should be developed for projected material costs. The purchasing department in preparing the schedule of materials procurement will use these. Scrap and rework allowances should be approached with the idea of bettering the performance of the past. At this stage of the planning process, the variable costs of manufacturing will be calculated based on Table 3.2.5.

The planners can now proceed to calculate the other important projections keyed to the profit and loss (operating) statement. These include

- Preliminary marginal income targets derived by subtracting variable costs from sales projections for each business unit or product
- Estimated period costs that can be distributed to business units or product lines on the grounds that if production were discontinued entirely, there would be no such costs
- Estimated period costs that cannot be so distributed

TABLE 3.2.5 Typical Variable Cost Elements

Cost	Expressed in	Source
Direct Labor	Per unit of product; total by quarter, by year	Cost system standards
Material	Per unit of product; total by quarter, by year	Cost system standards of usage, purchasing forecast cost
Indirect Labor	Variable portion per machine or direct labor-hour or other production measures	Graphic projection of standard crews at various volumes separating cost into fixed and variable portions
Expenses	Same as direct labor	Same as indirect labor

- A profit target for each planning unit or product derived by subtracting attributed period costs from marginal income, and a profit target for the company as a whole derived by totaling these targets and subtracting undistributed period costs.

Table 3.2.6 illustrates the brief profit and loss statement (P&L) format needed to display these proposed targets in the most effective form for decision making and communication. Horizontally, this presentation can be developed for the major categories of the business, such as industrial, consumer, and other categories. Alternatively, the P&L can be set up in terms of the corporate divisions, reflecting the specific profit center organization of the company. This approach will be particularly useful to individual managers. When necessary, the diffuse P&L estimates can be further broken down by product groups or product lines.

TABLE 3.2.6 Preliminary Plan and P&L: Company B

	($000)				
Income and expense category	OEM stock	OEM special	Customer stock	Customer special	Total company
1 Net Planned Sales	$70,000	$35,000	$85,000	$80,000	$270,000
2 Less: Variable Labor & Expense	$15,000	$6,000	$25,000	$20,000	$66,000
3 Variable Material	$20,000	$20,000	$25,000	$4,000	$69,000
4 = Total Variable Cost	$35,000	$26,000	$50,000	$24,000	$135,000
5 = Mfg. Marginal Income	$35,000	$9,000	$35,000	$56,000	$135,000
6 Marginal Income Percent	50.00%	25.71%	41.18%	70.00%	50.00%
7 Less: Mfg. Period Costs—Distributed	$6,000	$2,000	$13,000	$9,000	$30,000
8 Selling G&A—Distributed	$9,000	$3,000	$12,000	$11,000	$35,000
9 Total Distributed Period Cost	$15,000	$5,000	$25,000	$20,000	$65,000
10 Net Margin Before Common Costs	$20,000	$4,000	$10,000	$36,000	$70,000
11 Mfg. Period Costs—Common					$10,000
12 Common G&A					$20,000
13 Total Common Period Costs					$30,000
14 = Operating Profit Before Tax					$40,000
15 Operating Profit After Tax					$20,000
16 Average No. of Units	100,000	50,000	500,000	400,000	
17 Average Sales Price/Unit	$700	$700	$170	$200	

Note: G&A = general and administrative.

Balance Sheet Projections

In addition to the P&L targets, the planner must determine a group of targets based on the balance sheet. Table 3.2.7 shows the assets that Company B would require to meet the profit and loss statement targets of Table 3.2.6. To make such a forecast, the planners must work closely with the company treasurer and/or controller, who is primarily responsible for securing the funds for the necessary investment.

Accounts Receivables and Inventories

Two of the balance sheet items that the planner must forecast are directly related to sales: accounts receivable and inventories. The average investment, or balance, in accounts receivable will also reflect such things as customer payment practice and customary practice in the particular line of business. Like the P&L items, accounts receivable can be classified by product line, product group, division, or business unit.

Inventories are usually divided into three natural categories: raw materials, work-in-process, and finished goods. Each will have a target return consistent with the level of investment risk. Company policy, lead times, and turnovers should be taken into consideration in determining what balance in each category will be consistent with projected sales.

The remaining balance sheet items are fixed assets—and for some companies will include research and development (R&D) and proprietary investment—which are not directly related to sales. In forecasting for these items, the planner will have to begin by deciding on a method of valuation.

THE MODEL

Putting the model together

Both parts of the *preliminary plan*—the P&L items and the balance sheet projections—are now complete, and the planner has a separate set of tentative sales and marginal income targets for each division of the company and for each product group that it sells. The next step is to put together a model, which will enable the planners to analyze the forecasts of the preliminary plan in terms of rates of return on assets as well as contribution to total profits. To do this, the model compares the targets of the preliminary plan with targets developed by an alternate plan designed to yield a selected rate of return on each class of assets. The answer

TABLE 3.2.7 Preliminary Plan Balance Sheet by Business Segment: Company B

($000)

Asset	OEM stock	OEM special	Customer stock	Customer special	Replacement value	Book value
Accounts Receivable & Cash	$14,000	$5,000	$16,000	$15,000	$50,000	$50,000
Inventories:						
Raw	$2,500	$1,000	$4,500	$2,000	$10,000	
Work in Process (WIP)	$12,000	$3,000	$7,000	$3,000	$25,000	
Finished Goods	$7,000		$8,000		$15,000	
Total Inventories	$21,500	$4,000	$19,500	$5,000	$50,000	$50,000
Equipment & Buildings	$45,000	$4,000	$51,000	$60,000	$160,000	$90,000
Total Assets @ Replacement Value	$80,500	$13,000	$86,500	$80,000	$260,000	$190,000

section of the model will be the final guide for construction of a revised plan aimed at maximizing the return of assets.

The model provides the profit center manager with extensive opportunities to see what might be achieved by altering various elements under his or her control. Such "what if" questions will lead to a realistic final decision that should put performance close to the top of the profit range.

Computing Alternate ROA Targets

To compute the alternate ROA-based targets, the planners first determine the rates of return they expect on each of the balance sheet items of the preliminary plan: accounts receivable, inventories of raw materials, work-in-process, inventories of finished goods (property, plant, and equipment), research and development, and proprietary investments.

The expected rate of return shown in Table 3.2.8 will usually be different for each of these categories and could often be significantly different for two companies in the same line of business. For example, the expected rate on accounts receivable could vary from money market rates, to the prime lending rate of the banks, and on up to something much higher, depending on the credit rating of the customers involved. Target returns on property, plant, and equipment will be substantially higher because of the heavy long-term, low liquidity of the investment. Target returns on inventories will vary with the risk factors, such as shelf life and returns. The expected return on R&D and proprietary investments will depend on estimates of risk and assumptions about the useful life of the investment. Planners can often check their specified rates of return against the statistics, ratios, and return rates published by outside sources, such as trade associations, Robert Morris Associates, and Dun & Bradstreet.

Converting Rate of Return into Sales and Profit Targets

The next section of the model is a calculation designed to convert the rate of return targets into sales and profit targets comparable with those of the preliminary plan. The first step is to add the return on assets (ROA) assigned to each business unit or product to the distributed period costs allocated to it. The results are then added to give a total for the company. This total of ROA and distributed period costs is then compared with the marginal income that would be generated by the preliminary plan. The difference between the two represents the amount by which the targets based on ROA alone could fall short (as shown later in Table 3.2.10) of covering undistributed period costs and yielding the same profit as the preliminary plan.

The next step is to distribute this difference to the business units or products so that the final marginal income and profits of both plans will be the same. This distribution is necessary because marginal income, at the corporate level by definition, is the total of period costs plus profit. The purpose of the calculation, therefore, is to determine targets for each of the business units' marginal income that will

- Cover distributed period costs attributed to the unit
- Cover all common period costs
- Fulfill the return on assets targets for each
- Yield the same profit objectives as the preliminary plan

Table 3.2.9 shows a simple version of the model built for Company B. The first section consists of the forecasts of sales, variable costs, and marginal income for each business unit. The next section shows the target returns for each category of asset projected by the preliminary plan. This is followed by a calculation of the additional income required to bring the income estimated by the ROA method up to the levels of the preliminary plan. These additions to the

TABLE 3.2.8 Alternate Plan by Business Segment: Company B

($000)

Asset	OEM stock	OEM special	Customer stock	Customer special	Total company	Selected ROA
1 Accounts Receivable & Cash	$1,680	$600	$1,920	$1,800	$6,000	12.0%
Inventories:						
2 Raw	$300	$120	$540	$240	$1,200	12.0%
3 Work in Process (WIP)	$1,920	$480	$1,120	$480	$4,000	16.0%
4 Finished Goods	$1,820	—	$2,080	—	$3,900	26.0%
5 Total Inventories	$4,040	$600	$3,740	$720	$9,100	
6 Equipment & Buildings	$13,500	$1,200	$15,300	$18,000	$48,000	30.0%
7 Total ROA Dollars	$19,220	$2,400	$20,960	$20,520	$63,100	
Calculate additional ROA required						
						Line Source
8 Total Distributed Period Cost	$15,000	$5,000	$25,000	$20,000	$65,000	9 (Tbl. 2.6)
9 Add: Total ROA Dollars	$19,220	$2,400	$20,960	$20,520	$63,100	7
10 Total ROA plus Period Costs	$34,220	$7,400	$45,960	$40,520	$128,100	Total
11 Less: Marginal Income (MI)	$35,000	$9,000	$35,000	$56,000	$135,000	5 (Tbl. 2.6)
12 Additional ROA Required	$780	$1,600	$(10,960)	$15,480	$6,900	11 – 10
Calculate additional ROA allocation						
13 Variable Labor & Expense	$15,000	$6,000	$25,000	$20,000	$66,000	2 (Tbl. 2.6)
14 Variable Labor & Expense Percent	22.73%	9.09%	37.38%	30.30%	100.00%	13/Total 13
15 Additional Return Required	$1,568	$627	$2,614	$2,091	$6,900	14 × Total 12
16 Total ROA Required	$20,788	$3,027	$23,574	$22,611	$70,000	7 + 15

ROA targets are distributed on the basis of value added by each planning unit. The answer section at the bottom of the table shows the two approaches that would generate the same total profit for the company in distinctly different ways.

The model does not offer management an either/or choice between one approach and the other. It offers an opportunity to use comparative data for each business unit, product group, or product line to make choices that will provide the maximum possible benefit. For example, consider the targets for two products shown by the model in Table 3.2.10.

It is obvious that profits will be increased if management holds "customer special" at preliminary plan levels and attempts to increase the marginal income of "customer stock." But additional possibilities should be explored. Though customer special is a low market share operation, this may be because its products are overpriced. The figures show that there is room for a modest price cut, and if demand is price-elastic, this might stimulate a rise in volume that would increase total marginal income with a decrease in the marginal income ratio.

Similarly, with customer stock, management should consider a simple increase in prices to raise marginal income per unit. However, if the market response will reduce unit volume so much that total sales, measured in dollars, are reduced, a price increase will not be the best answer. In any case, the manager of the business unit should explore such possibilities as changing costs, altering product specifications, or changing the assets devoted to each product line. The model will show all the components of costs and investments attributable to the manager's unit. To increase the return, the manager should ask whether any of the following could be reduced:

TABLE 3.2.9 Target vs Actual Marginal Income Analysis by Product Group: Company B

($000)

	OEM stock	OEM special	Customer stock	Customer special	Total company
P&L					
Sales (Plan)	$70,000	$35,000	$85,000	$80,000	$270,000
Less: Variable Mfg. Cost of Sales	$35,000	$36,000	$50,000	$24,000	$145,000
Distributed Period Cost	$15,000	$5,000	$25,000	$20,000	$65,000
Common Period Cost					$30,000
Operating Profit/Tax					$40,000
ROA					
Accounts Receivable	$1,680	$600	$1,920	$1,800	$6,000
Inventories	$4,040	$600	$3,740	$720	$9,100
Equipment & Buildings	$13,500	$1,200	$15,300	$18,000	$48,000
Selected Return	$1,568	$627	$2,614	$2,091	$6,900
Total ROA	$20,788	$3,027	$23,574	$22,611	$70,000
Answer					
Distributed Period Cost	$15,000	$5,000	$25,000	$20,000	$65,000
Add: ROA	$20,788	$3,027	$23,574	$22,611	$70,000
Total Dist. Period Cost and ROA	$35,788	$8,027	$48,574	$42,611	$135,000
Less: Plan Marginal Income	$35,000	$9,000	$35,000	$56,000	$135,000
Target vs Plan Difference	$788	$(973)	$13,574	$(13,389)	$ —
Add: Plan Sales	$70,000	$35,000	$85,000	$80,000	$270,000
ROA Target Sales	$70,788	$34,027	$98,574	$66,611	$270,000
ROA Target Marginal Income	50.56%	23.59%	49.28%	63.97%	50.00%
Plan Marginal Income %	50.00%	25.71%	41.18%	70.00%	50.00%

- Investment in the product line
  - Receivables
  - Inventory
  - Equipment
- Variable costs in the product line
  - Materials
  - Labor
  - Expense
  - Marketing or sales expense
- Distribution costs

TABLE 3.2.10 Target vs. Actual Marginal Income Ratios by Product Group: Company B

	OEM stock	OEM special	Customer stock	Customer special
ROA Approach MI	50.56%	23.59%	49.28%	63.97%
Preliminary Plan MI	50.00%	25.71%	41.18%	70.00%
Marginal Income Differences	56.00%	–2.12%	8.10%	–6.30%

The profit center manager can also see how product relates to other products or segments of the company. This may reveal opportunities to increase profits by altering the product mix. For example, where the same equipment is used in manufacturing two products, changing the priorities in equipment utilization may facilitate output of the product with the higher return.

Adding Other Profitability Measures

Other measures can be added to the model to give the profit center manager a better understanding of the choices that are available. For example, when a company is operating at capacity, it is more realistic to think in terms of profits per hour than profits as a percent of sales. The necessary figures can be shown on the model as

- ROA targets marginal income per hour
- Preliminary plan marginal income per hour

THE POWER OF THE MODEL

Use in Goal Setting

The model can be used at all marketing levels of the organization (corporate, business unit, product line). Goal setting can be done from the top down or from the bottom up—from corporate to product or from product to corporate. The president may look at a total business unit and ask, "How can this unit be made more profitable?" Or the product manager may ask, "What can be done to make this product more profitable?" In either case, the model is designed to deal with the chain of more specific questions that each of the broader questions generate. The answers, showing the effect on division profit, can then be transmitted to different levels of the organizational hierarchy.

Other typical questions that the model will answer include

- How can I use my capacity more profitably?
- What effect will my mix of sales (by either division, plant, product line, or product) have on my profits?

The model is designed to quantify the considerations involved in this kind of evaluation. It gives the various profit centers a common set of measures for communication.

The first consideration in addressing such questions is price and market share. If product sales managers can tell whether a price increase or decrease will be accompanied by an increase, decrease, or no change in volume, the model can evaluate various strategies in terms of marginal income, capacity utilization, and the final effect on profits.

The "What If" Matrix

In addition to listing all "what if" questions, the profit planners may construct a matrix with three major constraints and six major questions. Figure 3.2.2 shows a simple matrix. In a more complicated version with three constraints and six questions, there will be boxes on the grid where significant answers appear to proposed actions. (In three boxes one of the constraints rules out the action that one of the questions proposes, and no answer will be possible.) Of course, the model can also assimilate all combinations of what if questions under each constraint, and it can work on the assumption that profit can vary without constraint.

TABLE 3.2.11 Model Plan Elements—"What If" Analysis

Preliminary plan	"What if" capability	Revised plan
P&L	1. What if variable manufacturing costs increase or decrease?	P&L
	2. What if variable marketing costs increase or decrease?	
	3. What if distributed period costs increase or decrease?	
	4. What if common period costs increase or decrease?	
Balance Sheet	5. What if asset balances are increased or decreased?	Balance Sheet
	6. What if target return on assets employed are increased or decreased?	
	Selecting three different constraints	
ROA Selection	1. Holding unit sales price and profit constant—but unit sale price varies.	Revised
MI%_______	2. Holding unit volume and profit constant—but unit sale price varies.	MI%_______
ROA_______		ROA_______
	3. Holding unit sales price and unit volume constant—but profit varies.	
P/ECE______		P/ECE______
P/S_________	Resulting in__________________________	P/S_________

The what if matrix is one of the analytical tools that the model makes available to the planner. Its purpose is to take the blind gambles out of planning and base each decision on scientific analysis and full information about the company's operations. Using actions and assumptions similar to those of Table 3.2.12, the matrix can and should be used to develop a final plan for the period ahead that will bring company profits closer to their potential maximum than either the preliminary plan or the ROA approach alone.

PROFIT PLANNING IN ACTION

On the basis of the model it has constructed (Table 3.2.8) and various what if studies, Company B decides to make some important changes in the targets projected by the preliminary plan (Table 3.2.11).

- In customer stock items, the management decides to increase material specifications, even though this means a 10 percent increase in cost. This will lift the variable material costs from \$25 million to \$27.5 million. In addition, the company plans to add value to the product by tightening up on inspection and improving the quality of workmanship. This will raise labor cost 10 percent, from \$25 million to \$27.5 million. The company forecasts that improved quality will justify an increase of 8 percent in selling price. As a result, planned sales go up from \$85 million to \$91.8 million (8 percent increase).
- In customer special items Company B determines that it will cut unit sales prices by 15 percent. As the model shows, this will bring marginal income more in line with the marginal

TABLE 3.2.12 Revised Plan—Company B—Actions and Assumptions by Product

Product	Revised plan action	P&L result	Balance sheet result
Common Stock	Change product specifications	Increase variable cost 10% (from $25 to $27.5 million)	Increase inventory value 10% (from $19.5 to $21.45 million)
	Improve quality	Increase variable labor cost 10% (from $25 to $27.5 million)	Increase selling price by 10% (from $85 to $91.8 million)
	Increase inventory turnover	No change	Decrease inventory value 50% (from $21.45 to $10.725 million)
	Change price structure	Increase sales by 8% (from $85 to $91.8 million)	Increase accounts (from $15 to $16.2 million)
	Change to cash and carry	No change	Eliminate accounts receivable (from $16.2 to $12.75 million)
Customer Special	Lower ROA to control competition	Decrease sales price by 15% (from $200 to $170 per unit)	Decrease accounts receivable value 15% (from $15 to $12.75 million)
	Increase market share	Increase sales 30% (from $80 to $88.4 million)	Increase accounts receivable 30% (from $12.75 to $16.575 million)
		Variable labor and material increase by 30% (from $24 to $31.2 million)	Increase inventory by 30% (from $5 to $6.5 million)

income ratio derived by the ROA approach. Unit sales price will come down from $200 to $170 per unit, and as a result, Company B foresees an increase of 30 percent in volume. This will bring sales volume to $88.4 million. Labor and expense costs will go up for $4 million to $5.2 million, giving a total variable cost of $31.2 million.

The net result of these changes is to drop the marginal income ratio on customer stock, from 41.2 to 40.1 percent and to lower the marginal income ratio for customer special from 70 to 64.7 percent. However, total marginal income of the company has increased from $135 million to $138 million, and profit before taxes is now $43 million instead of $40 million. In both cases, the marginal income ratio is lower, but volume has increased and assets are being used more efficiently. As a result, profit is higher. Table 3.2.13 shows how these moves have changed the targets and predicted profits.

The next step is to look at the balance sheet to see what changes can be made and what changes the new sales forecast will involve. Table 3.2.13 shows the results of this analysis. Management has decided to reduce the accounts receivable for customer stock items from $16 million to zero. In effect, it is making customer stock items a cash and carry business. At the same time, Company B proposes to increase the inventory turnover on customer stock items by 50 percent. This could be expected to reduce raw material inventories by $2.25 million, work-in-process by $3.5 million, and finished goods by $4 million. However, the planned upgrading of raw materials (resulting in a 10 percent cost increase) and workmanship in this area partially offset the reduction in quantities, and so the final inventory item on the balance sheet for customer stock will be $10.725 million.

In customer specialty items, Company B expects to increase accounts receivable by the same percentage as the expected increase in sales. The increase of $1.575 million brings total accounts receivable to $16.575 million. At the same time, it is necessary to increase total inventory value to reflect the higher total variable costs associated with larger volume. Applying the

TABLE 3.2.13 Revised Plan & P&L Based on Assumptions ("What if Capability"): Company B

($000)

Income and expense catagory	OEM stock	OEM special	Customer stock	Customer special	Total company
1 Net Planned Sales	$70,000	$35,000	$91,800	$88,400	$285,200
2 Less: Variable Labor & Expense	$15,000	$6,000	$27,500	$26,000	$74,500
3 Variable Material	$20,000	$20,000	$27,500	$5,200	$72,700
4 = Total Variable Cost	$35,000	$26,000	$55,000	$31,200	$147,200
5 = Mfg. Marginal Income	$35,000	$9,000	$36,800	$57,200	$138,000
6 Marginal Income (MI) Percent	50.00%	25.71%	40.09%	64.71%	48.39%
7 Less: Mfg. Period Costs—Distributed	$6,000	$2,000	$13,000	$9,000	$30,000
8 Selling G&A—Distributed	$9,000	$3,000	$12,000	$11,000	$35,000
9 Total Distributed Period Cost	$15,000	$5,000	$25,000	$20,000	$65,000
10 Net Margin before Common Costs	$20,000	$4,000	$11,800	$37,200	$73,000
11 Mfg. Period Costs—Common					$10,000
12 Common G&A					$20,000
13 Total Common Period Costs					$30,000
14 = Operating Profit Before Tax					$43,000
15 Operating Profit After Tax					$21,500
16 Average No. of Units	100,000	50,000	500,000	520,000	
17 Average Sales Price/Unit	$700.00	$700.00	$183.60	$170.00	

variable cost increase of 30 percent to raw material inventories of $3 million and work-in-process of $2 million brings total inventories for customer specialty business to $6.5 million. Table 3.2.14 shows the balance sheet entries associated with the revised plan. The changes have resulted in a decline in the replacement value of assets from $260 million to $238.3 million. If management chooses to use book value to estimate its investment, the decline will be the same dollar amount, bringing the total down from $190 million to $168.3 million. Either way, the amount of capital on which the company must earn a return is reduced by $21.7 million.

Putting it all together, Company B arrives at its revised plan. Table 3.2.15 shows how the new figures compare with the targets set by ROA analysis. No significant change has been made in OEM stock items or OEM specialty items because the original projections of marginal income were close enough to the ROA targets to indicate that the proposed prices would provide satisfactory yields.

TABLE 3.2.14 Revised Plan Balance Sheet by Business Segment: Company B

($000)

Asset	OEM stock	OEM special	Customer stock	Customer special	Replacement value	Book value
Accounts Receivable & Cash	$14,000	$5,000	$ —	$16,575	$35,575	$35,575
Inventories:						
Raw	$2,500	$1,000	$2,475	$2,600	$8,575	
Work in Process (WIP)	$12,000	$3,000	$3,850	$3,900	$22,750	
Finished Goods	$7,000		$4,400		$11,400	
Total Inventories	$21,500	$4,000	$10,725	$6,500	$42,725	$42,725
Equipment & Buildings	$45,000	$4,000	$51,000	$60,000	$160,000	$90,000
Total Assets @ Replacement Value	$80,500	$13,000	$61,725	$83,075	$238,300	$168,300

TABLE 3.2.15 Revised Plan Move—Target Selling Prices and Target Marginal Income: Company B

($000)

	OEM stock	OEM special	Customer stock	Customer special	Total comany
P&L					
Sales (Plan)	$70,000	$35,000	$91,800	$88,400	$285,200
Less: Variable Mfg. Cost of Sales	$35,000	$26,000	$55,000	$31,200	$147,200
Distributed Period Cost	$15,000	$5,000	$25,000	$20,000	$65,000
Common Period Cost					$30,000
Operating Profit/Tax					$43,000
ROA					
Accounts Receivable	$1,680	$600	$ —	$1,989	$4,269
Inventories	$4,040	$600	$2,057	$936	$7,633
Equipment & Buildings	$13,500	$1,200	$15,300	$18,000	$48,000
Selected Return	$2,637	$1,055	$4,835	$4,571	$13,098
Total ROA	$21,857	$3,455	$22,192	$25,496	$73,000
Answer					
Distributed Period Cost	$15,000	$5,000	$25,000	$20,000	$65,000
Add: ROA	$21,857	$3,455	$22,192	$25,496	$73,000
Total Dist. Period Cost and ROA	$36,857	$8,455	$47,192	$45,496	$138,000
Less: Plan Marginal Income	$35,000	$9,000	$36,800	$57,200	$138,000
Target vs Plan Difference	$1,857	$(545)	$10,392	$(11,704)	$ —
Add: Plan Sales	$70,000	$35,000	$91,800	$88,400	$285,200
ROA Target Sales	$71,857	$34,455	$102,192	$76,696	$285,200
ROA Target Marginal Income	51.29%	24.54%	41.18%	59.32%	48.39%
Plan Marginal Income %	50.00%	25.71%	40.08%	64.71%	48.39%

The ROA target return for customer stock items has to be changed because of the decision to reduce the assets required for this part of the business. The target marginal income therefore drops from 49.2 percent of sales to 46.2 percent. At the same time, marginal income as projected by the revised plan drops from 41.2 to 40.1 percent. The gap between the ROA target and the planner performance remains, but it has narrowed by one quarter—from 8 to 6 percent.

In customer specialty items, the revised plan provides for a price cut that will lower marginal income from 70 to 64.7 percent. This is 4.4 percentage points ahead of the revised ROA target, but again the gap has narrowed. It was a full 6 points when the preliminary plan was compared with the first ROA target.

For the company as a whole, the revised plan drops marginal income from 50 to 48.4 percent. But since sales increase by $15 million, profit before taxes rises from $40 million to $43 million.

Table 3.2.16 shows how the revised plan compares with the preliminary plan. The return on assets increases from 21 to 25.5 percent, which brings it very close to the 27 percent that Company A reported in Table 3.2.1. The after-tax profit to equity capital employed ratio rises from 20 to 27.5 percent, which puts it ahead of the 23 percent ratio of Company A. This reflects the fact that Company B has maintained the same level of borrowing in relation to a lower equity capital employed value and has increased income at the same time. The margin of safety for Company B—the percentage by which operations will exceed the break-even point—rises from 29.6 to 31.8 percent. The break-even point itself is up from sales of $190 million to

TABLE 3.2.16 Comparison Preliminary and Revised Plan: Company B

($000)	Plan	Revised	Difference	
Balance sheet				
Assets	$190,000	$168,300	$(21,700)	Decreased
Liabilities	$90,000	$90,000	—	No Change
Equity Capital Employed	$100,000	$78,300	$(21,700)	Decreased
Income statement				
Net Plan Sales	$270,000	$285,200	$15,200	Increased
Variable Mfg. Cost of Sales	$135,000	$147,200	$12,200	Increased
Total Marginal Income	$135,000	$138,000	$3,000	Increased
Period Mfg.	$40,000	$49,200	$9,200	Increased
= Cost of Sales	$175,000	$187,200	$12,200	Increased
Period Selling G&A	$55,000	$55,000	—	No Change
= Net Operating Cost	$230,000	$242,200		Increased
Profit Before Tax	$40,000	$43,000	$3,000	Increased
Profit After Tax	$20,000	$21,500	$1,500	Increased

$196.28 million. Under the revised plan, Company B is leaner, more efficient, and more profitable than it would have been if planning had stopped with the preliminary plan.

Use of the model as a planning tool applies at all levels of a company. As Table 3.2.17 shows, the targets can be set not only by business segments or divisions but also by product groups and then by each individual product. Information flows up and down the corporate hierarchy, with everyone looking at the same kind of model and with each level making the decisions that are within the scope of its authority.

The power of the model does not lie in comparison of projected sales and marginal incomes with targets that will yield a satisfactory ROA. Anyone can say, "I propose to sell my products at a price that will give me an equal return on each of the investments I made and yield a satisfactory ratio of profit to equity capital employed." It enables people to examine the figures and determine what products are out of line and what can be done about it. The model is simply a device for bringing the experience, knowledge, and intelligence of people at every level into focus.

Selling the Idea of Planning

The industrial engineer or other expert who wants management to take the systematic approach to provide planning will often encounter these objections:

- It takes too much executive time.
- Our business is different; we cannot forecast sales.
- Our company is too small to afford this sort of planning.
- We are making good profits now, and we don't need to plan changes.

These statements may be true, but they tell more about weaknesses in the company's way of doing business than about its need for planning. Top executives and supervisors should be asked to make only key decisions. Detailed schedules prepared by the engineers and accountants should give them all the information they need. A properly designed and administered

BUDGETING AND PLANNING FOR PROFITS

TABLE 3.2.17 Hierarchy of Model Applications

Level 1 CORPORATE BY BUSINESS SEGMENT OR DIVISION

	Segment	Segment	Segment	Segment	Total
Marginal Income					
Distributed Cost					
P&L					
ROA					

Overall Planning
and Control

Level 2 BUSINESS SEGMENT OR DIVISION BY PRODUCT GROUP

	Product Group	Total
Marginal Income		
Distributed Cost		
P&L		
ROA		

P&L Responsibility
Marketing Strategy
Comparision to
Industry Ratios
Capital Investment
Planning

Level 3 PRODUCT GROUP BY PRODUCT

	Product Group	Total
Marginal Income		
Distributed Cost		
P&L		
ROA		

Capacity Defined
Product Pricing Target

planning system will make far better use of executive time than a catch-as-catch-can system of decision making.

The company that cannot accurately forecast sales—a manufacturer of high-end-type products, for instance—can at least have a forecast as good as the toughest competitor's. And the executive needs, just as much as in any other company, to make the best possible use of resources.

Nor is planning a tool for the medium- and large-sized firm alone. Small companies need good planning and associated cost accounting as much as big companies. Knowing their cost structure may make the difference between life and death. And with adequate cost identification, planning will not add materially to expenses.

Finally, because a company is doing well does not mean that it could not be doing better, or that it will always do well without any changes or review of its performance. This argument is likely to be heard from companies in a new, fast-growing industry where there is a temporary shortage of capacity. But yesterday's new industries are likely to be the scene of today's bloodletting. The electronics business, for instance, has been immensely profitable for some companies and fatal to others. The booming period is likely to be followed by hard times when strict control of costs and a clear view of the "what if" possibilities will be the key to survival.

There is no company—large or small, prosperous or hard-pressed—that cannot benefit by the information and understanding that the model gives its management.

SUMMARY

The purpose of profit planning is to maximize profits—not just dollar volume of profits but also the ratio of profits to equity capital employed. That is to say, profit planning is designed to ensure the largest possible return on investment to the stakeholders.

BUDGETING AND PLANNING FOR PROFITS

Effective profit planning is a comparatively simple and straightforward set of forecasts. The systems and procedures of planning should be designed to simplify and clarify the process of setting goals for the organization. A mass of uncoordinated forms and statistical reports is not planning: it is pointless busywork.

This chapter has described the construction of a highly effective planning model and a variance control system to back it up. Beginning with a set of preliminary estimates of sales, costs, and marginal income, the model compares the results of this plan with goals developed by an alternate using a return on assets approach. Management can then use the model to explore the possibilities of changing the product mix, altering the price structure, reducing or increasing investment, or reducing costs by redesign of the product. The final plan that it adopts will offer the realistic prospect of yielding total profits for the organization close to the top of the range of possibilities.

Plans cannot be cast in stone. Changing circumstances may cause the forecast on which the plan was based to become outdated. Good planning procedures call for periodic review and revision to take account of such developments.

It is a mistake, however, to change a plan simply because performance is not measuring up to expectations. The control system should identify every significant variance from planned targets and initiate immediate action to eliminate the causes.

Planning and ensuring that performance measures up to targets is management's first and most important function. But planning need not be a burden on top management. The system can be set up so that the chief officers of the company make only the broad, fundamental decisions. Profit planning enables the top people to concentrate on the vital questions of how the company can make the best possible use of the resources at its command and how it can keep expanding and strengthening its position in the future.

All good planning systems will have two things in common: They will set up realistic targets, and they will provide the machinery for making actual performance conform to these targets. Planning is not just a hopeful forecast of what the future will bring. It is a method of setting goals to maximize profits and guiding the operations of the company firmly toward these goals.

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BIOGRAPHY

Edmund J. McCormick, Jr. has served as chairman of McCormick & Company, an international consulting firm founded in 1946 that specializes in strategic planning, management consulting, financial advisory, profitability studies, cost control, and training. He is a recognized specialist in strategic planning, turnaround, and business engineering and is the author of numerous papers and articles on planning, securitization, budgeting, cost control, and profitability. Mr. McCormick has served on the board of directors of Room Plus, Inc. and Kirlin Holding Corporation. He is currently a director of Greenleaf Partners II, LLC as well as a comanager of Greenleaf Capital Partners, LLC. Mr. McCormick attended Carnegie-Mellon University in Management Studies and holds a B.S. in finance and accounting from Long Island University. He is a graduate of Valley Forge Military Academy.

Source: MAYNARD'S INDUSTRIAL ENGINEERING HANDBOOK

CHAPTER 3.3

COST ACCOUNTING AND ACTIVITY-BASED COSTING

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This chapter will discuss how industrial engineers can use a modern cost methodology—activity-based costing (ABC)—as a fundamental tool to analyze costs in the age of technology in order to regain competitiveness with foreign and domestic manufacturers and service providers. Old cost accounting systems no longer work and may even provide management with misleading information. This chapter will give industrial engineers examples of how to modernize companies' cost systems by relating resources to their consuming activities. It will compare and contrast ABC to traditional cost systems, give actual examples of ABC in action, and show the evolution of cost systems in American business.

BACKGROUND

Technology Advances Transform Manufacturing Methods

A revolution is taking place in manufacturing and service sectors throughout the country. Technology is rapidly transforming traditional manufacturing methods and service delivery systems. The result has been a dramatic change in ratios between fixed and variable costs that continue to surge at alarming rates. As fixed costs climb, they are wreaking havoc on profit margins, making them extremely vulnerable to competitive forces.

To compete in today's dynamic and rapidly changing global marketplace, our domestic firms need new leadership to understand and control their overhead costs as in no other time in our history. No professional is better equipped to provide this direction than the industrial engineer. Thus, the gauntlet has been thrown down to our industrial engineering cadre to meet this critical challenge of the new millennium.

During the past decade, industrial engineers have made enormous contributions to productivity through the introduction and installation of production, quality improvement, and waste elimination programs—for example, just-in-time (JIT), manufacturing resource planning (MRP), computer-aided manufacturing (CAM), and computer-integrated manufacturing (CIM). Many of these were developed offshore and adopted in this country to enable domestic firms to compete with overseas producers, especially Japan, but also the emerging European Community. Unfortunately, even after the implementation of these techniques, regaining competitiveness has still been elusive. The question is, "If so many domestic manufacturers and service companies have adopted advanced manufacturing and service delivery methods, why are they still languishing behind in world competition?"

The answer lies in the integration of technology with modern information and control systems. In spite of advanced manufacturing technology, many companies have failed to make their financial, managerial accounting, and costing systems conform with the changes in their manufacturing and service environments. Maintaining the financial costing system has traditionally been the responsibility of the cost accountant. Unfortunately, most cost accountants have been isolated from the changes that have been occurring on the factory floor. Those few who have understood their impact have been reluctant to introduce the needed system changes.

Accounting Education Lags Behind Management Information Needs

Accounting education has remained virtually unchanged for decades, notwithstanding the changes in information needs throughout the organization. Such education might have been satisfactory in the less mechanized world of the 1960s and 1970s. But as advanced technology was introduced and labor was displaced with fixed-cost machinery and electronics, the cost accountants were left without the tools to make the transition. They did not have a clear understanding of how technology was invalidating their firms' cost systems. Without such knowledge, a severe gap developed, leaving cost systems outmoded, outdated, and worse. Worse because in many instances the old systems provided management information entirely inadequate for decision making. Now there is a better way.

WHAT IS ABC?

Activity-based costing (ABC) attributes variable, fixed, and overhead costs directly to each product or service by using the *activities* required to produce the product or service as the means of allocation. With ABC, the cost of a product or service equals the cost of raw materials plus the sum of the costs of all activities used to produce the product or service.

Activity-based management (ABM) is a system utilizing activity-based costing plus a number of control elements. These consist of process value analysis, activity-based process costing, activity-based product costing, performance measurement, and responsibility accounting.

ABC VERSUS TRADITIONAL COSTING

Traditional costing accumulates the cost of raw materials and direct labor, then applies overhead using an arbitrary allocation factor such as the volume of production. As a result of a new understanding of how products and services consume activities and, in turn, how activities consume resources, ABC uses a different cost-attachment process.

Activity-based costing relates resources to the actual activities that consume them. Conventional wisdom states that the production of a product or service produces costs. More accurately it is the *activity* involved in the production of a product or service that creates the cost.

If we agree that an activity involves cost, then it follows that the actual cost of a product or service should be the sum total of the costs of each activity required to produce it. By breaking down product cost according to individual activities or events, costs can be controlled by managing each of the activities and/or the events that cause the cost-consuming activity.

Similarities to Traditional Systems

The activity-based cost system has a number of similarities to traditional systems. It, too, is a two-stage allocation process. However, in the second stage of the allocation process the two systems diverge. Figure 3.3.1 shows how a simple model of an ABC system might operate. As examples, two activity centers—customer service and purchasing—are illustrated for the New England China Company. Of course, in practice, an ABC system would contain many more activity centers.

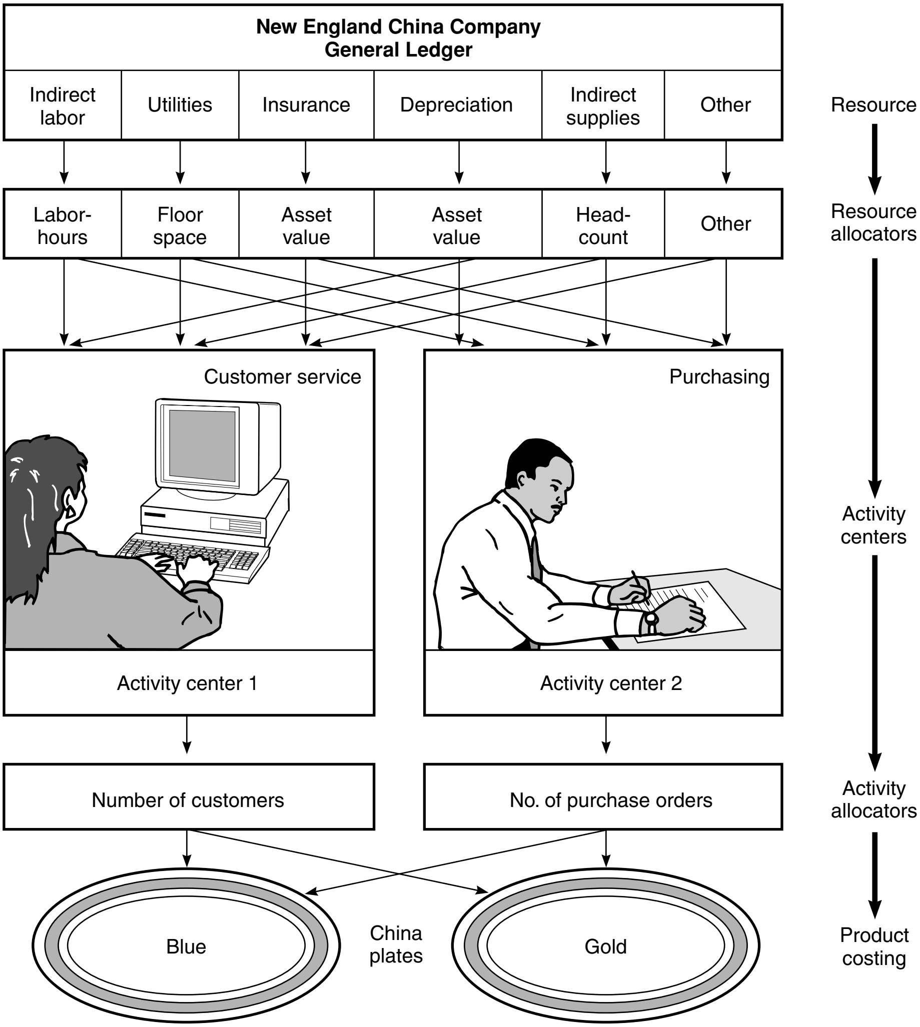
New England China Company
General Ledger
Indirect labor
Utilities
Insurance
Depreciation
Indirect supplies
Other
Labor-hours
Floor space
Asset value
Asset value
Head-count
Other
Customer service
Purchasing
Activity center 1
Activity center 2
Number of customers
No. of purchase orders
Blue
China plates
Gold
Resource
Resource allocators
Activity centers
Activity allocators
Product costing

FIGURE 3.3.1 Absorption-based overhead allocation method.

The upper portion of the example shows the general ledger accounts (*resources*). At this early stage, these accounts would be reviewed to determine which resources are consumed by which activities. In this example, the activities are customer service and purchasing. The next step is to determine the method of attributing these resources to the activities. Often called *first-stage cost drivers* in the literature, the term *resource drivers* is used here for clarity.

In the example, the resource—indirect labor—can be attributed to both activities based on the *resource driver:* labor-hours. That is, the number of labor-hours will determine the amount of indirect labor consumed by the activity of customer service and purchasing. This is the direct linear relationship we are looking for.

The allocation of utilities proves to be a bit more challenging. In the absence of metering, which of course is the best answer, a resource driver must be found that provides the linear relationship for the consumption of this activity. Head count or the number of labor-hours could be used. However, they would not provide these two activities with the linear relationship that is needed and therefore would provide less-than-optimum results. Floor space is the best fit. Although it is not as precise as a meter, it is the most cost-effective resource driver for this purpose.

The Second-Stage Difference

Once these costs are assigned to the newly identified cost pool within the activity center, we are ready for the second stage. The second stage is the assignment of the amount of an activity consumed by the product or service. This process, often referred to as the *second-stage cost driver,* will be called *activity driver* here. In the case of the purchasing activity, we have chosen an activity driver based on the number of purchase orders. That is, the amount of the purchasing activity that a product (e.g., a china dish) consumes is directly related to the number of purchase orders generated to produce that pattern of china dishes. The customer service activity can be directly related in the same way by using the number of customers as the activity driver.

Unlike in traditional costing, the second stage of the cost assignment process is not an arbitrary one. ABC does not allocate overheads based on one or two arbitrary methods, such as percentage of direct labor, material, and/or machine hours, that have little or no relationship to how a product uses the overhead services. Instead, ABC systems identify how these resources are consumed by each product or service and attach values according to this consumption pattern. There is very little indirect cost in an ABC system, since most costs can be directly attributed to the product or service.

BENEFITS OF ABC

An ABC system has the benefit of being a highly effective control tool. As was stated earlier, traditional systems and thinking maintain that the production of a product or a service actually creates cost. That view examines cost *after* it has been incurred. It is easy to see that cost, once expended, cannot be controlled (modified). Traditional control systems rely on examining variances that are nothing more than a review of historical data. Such a system reveals only whether a plan has been under- or overachieved. Control in these instances relies on making adjustments after the fact in order to bring the potential for significant variances closer to plan at some time in the future.

Activity-based management examines cost in a new, more controllable way. As was stated earlier, products and services consume activities and, in turn, activities consume resources. Therefore, the cost of all products and services is the total cost of all the activities consumed by the product or service.

In engineering terminology, to *control* means to regulate. Typically, regulating is accomplished by comparing an actual or real-time statistic with a standard. The resulting variance between the actual and the standard determines the amount of adjustment required to bring a process back to the standard. Cost containment is usually the prime target of control, and the regulation of cost under traditional systems means that cost must exceed a standard before the control system is able to spot it in order to take corrective action. By their very design, traditional systems must encounter cost overages before any corrective action can actually be taken.

We have seen that the ABC system focuses on activities rather than costs. By organizing the work process into distinct activities, a significant control advantage is gained. Controlling activity, rather than cost, is the objective of the ABM.

In ABM systems, control begins by separating activities into value-added and non-value-added categories. If a value-added activity is being consumed, costs may be increasing, but so is value. If a non-value-added activity is increasing, so are costs, but with no added benefit. Therefore, an important aspect of the ABM system is to report both categories so that managers can see how their outputs impact the two basic activities. Control is almost automatic, as managers are provided with the opportunity to see activities in their areas of responsibility as value-added and non-value-added. They will place emphasis on the value-adding component.

WHY SWITCH TO ABC SYSTEMS

The purpose of ABC is to remove the distortions caused by traditional costing systems, such as absorption-based and direct costing. These traditional systems were adequate when direct labor costs were a large percentage of product cost. However, there are few operating environments today where these older cost systems cannot be supplanted by an ABC system to provide more meaningful product or service costs. That is because activity-based management takes the best attributes of absorption-based and direct costing and applies all indirect costs to products and services by analyzing the activity that actually produces the particular cost. This method treats all costs as if they were *variable.*

Absorption-Based Accounting Is Imprecise and Misleading

The majority of domestic firms continue to use absorption-based accounting systems for product costing. A recent study by the University of Rhode Island reported that 62 percent of the firms surveyed did not differentiate between fixed (period) and variable costs (the direct costing method). In addition, 93.7 percent still applied overhead on the basis of direct labor (the absorption method).

Why such is the case in the face of compelling evidence against the absorption-based costing method is not easy to ascertain. A reason often offered is that absorption-based accounting is the method required for external financial reporting needed by the IRS, the SEC, stockholders, and the like. Having an absorption-based system already in place, management may be reluctant to make significant changes or to run two systems (internal and external) at the same time. Management may feel that it is more cost effective simply to modify the external system for internal reporting purposes, unaware of the potential for many information systems reporting inaccuracies.

As was noted earlier, in the past, manufacturing processes were more labor-intensive, overhead was a small percentage of total cost, and the range of products (product diversity) was more limited. Therefore, a decision to modify the traditional system for costing purposes did not cause severe harm. However, with the move toward automation, where labor costs are often less than 10 percent of production and overhead reaches toward 50 percent of the total cost or higher, direct labor can no longer be used as the method of allocating value to a product or service.

In organizations with considerable product diversity, product and service costs may be severely distorted. The unit cost of a high-volume run of a product will appear greater than that of a low-volume run. In realty, this is not true, but the inherent system flaws compel the numbers to be reported that way. Simple mathematics will demonstrate that though the cost of setup, material handling, purchasing, and the like may be the same on two production runs, the unit cost for a higher-volume run compared with a lower-volume run will be greater. However, the traditional method takes all these indirect costs, totals them, and then allocates the cost using labor-hours or some other volume-based unit. Because the higher volume run has more labor-hours, it is assigned more of the cost.

Since these costs do not vary on a per-unit basis, they cannot be accurately accounted for in any system that bases cost on production volume. That is why management reports will show (incorrectly) low-volume products as being more profitable than a high-volume products. Whole product lines have been discontinued because of this fallacious reasoning.

As an example, Alcoa was prepared to close an important West Coast division after receiving negative margin reports from an outdated management information system. Most of the senior management was in agreement—close it down. However, the vice president of engineering had a number of suspicions concerning the numbers. He convinced management to reconsider while a team was sent to review cost allocations. After a basic activity-based analysis was completed, the division showed margins that were surprisingly acceptable.

The traditional method assumes that only volume-related bases such as labor-hours, machine hours, and material dollars are used to allocate overhead to products or services. Allocations based on units of production (direct labor, machine hours, material) falsely assume that the cost of production varies in direct proportion to the number of items produced. This assumption may be true for direct costs (e.g., for certain labor, material, and supplies), but the costs of inspection, setup, engineering, and purchasing, which are not volume-related, vary with the number of inspections, setups, engineering changes, and purchase orders. Allocating non-volume-related costs requires the use of a cost base that is *non*-volume-related. Figure 3.3.2 demonstrates how a traditional system reports product margins, giving high-volume products the appearance of lower margins and low-volume products the appearance of higher margins.

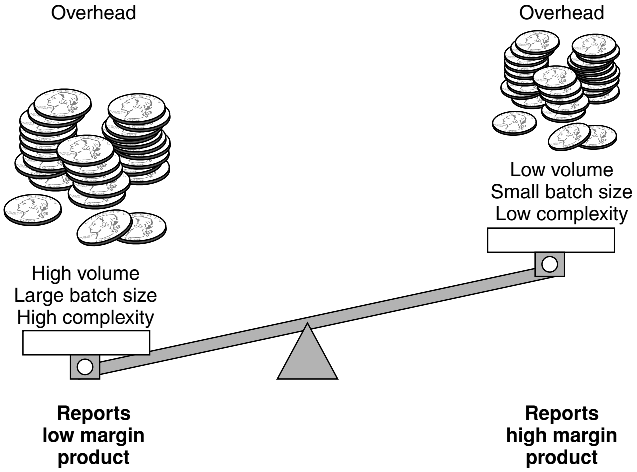

FIGURE 3.3.2 The direct costing or marginal income (MI) method removes all indirect costs from the production and services. By subtracting variable costs from sales revenues, the result will be MI. Relative profitability is made much clearer when the marginal income of each product or service is compared. Overhead is shown below the line. MI is used to cover overhead. The remaining MI is profit. If there is not sufficient MI to cover the overhead, the remainder is negative, amounting to a loss.

Direct Costing Is an Improvement on Absorption-Based Costing

Over the past several decades, direct costing, also known as *marginal costing,* was installed by a number of leading-edge companies in an attempt to overcome some of the weaknesses of the absorption-based system. This method of costing separates cost, by behaviors, into fixed and variable components. By subtracting variable cost from sales revenue, a number referred to as *marginal income* (MI) is obtained. By using direct costing decisions and analysis, managers get a more realistic picture of relative profitability. Figure 3.3.3 shows a model of overhead allocation in a marginal income system. Overhead is treated by removing it from consideration in the variable cost of production. In this method, overhead is said to be shown *below the line.*

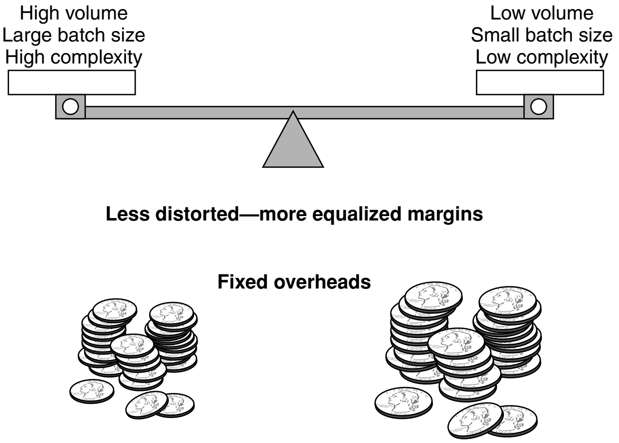

FIGURE 3.3.3 Activity-based costing significantly affects gross margins of the highest and lowest volumes, batch sizes, and complexity ranges of products and services. Those that fall within a midrange will also be affected, but not as radically. Comparing this with Fig. 3.3.4 demonstrates that ABC has the opposite effect in the assignment of overhead burdens. By correctly identifying which products receive these indirect costs, product and service costs take entirely different values compared with absorption-based and direct costing. These are the true product and service costs.

Disenchantment with Marginal Costing

Many managers prefer to rely on full costing rather than on direct costing. Some maintain that salespersons would be tempted to cut prices closer to margins if they knew their variable costs. The use of full costing actually eliminates this temptation by obfuscating true costs. Second, since fixed costs are not factored in, a number of managers feel that variable costs do not adequately reflect the demands placed by different products on fixed resources such as plant and equipment. These managers are reluctant to drop products and services because of their concern regarding unabsorbed overhead, which would decrease total profits.

After all, product- and service-related decisions for introduction, pricing, and discontinuance should be long-term decisions, strategic in nature. Marginal income is based primarily on variable and incremental costs that, by definition, are short term. Marginal costing made sense when variable costs (labor, material, certain overhead costs) were a larger proportion of the total manufacturing cost. We know that this is no longer the case.

Evolution of a "New" Cost System

Although the latter part of the 1980s saw a surge of interest in activity-based costing, the principles have been available for 70 years. The concept for the ABC system was first advanced by C. Hamilton Church in the early 1920s. ABC never caught on, as it was difficult to implement owing to the large volume of transactions that needed to be recorded by hand. Only after the widespread availability of computers and spreadsheet programs could ABC provide a cost-effective solution to the tediousness of manual recording.

Activity-based costing is certainly a novel way to look at costs, yet it has all the elements of an absorption-based system. The basic difference is that overhead is directly traced to the product or service instead of pooled and applied across product and services using an arbitrary formula (percentages of labor-hours, machine hours, etc.). Cost tracing first starts by identifying all the support activities required for production, then determining how the product actually consumes the various supporting activities. In that way, all overhead costs are attached directly to the product or service that consumes them. Figure 3.3.4 shows how overhead allocations are almost opposite in magnitude from the allocations produced under the absorption-based system in Fig. 3.3.2. Figure 3.3.4 allocations are more accurate reflections, since they are based on how they are consumed by the product or service.

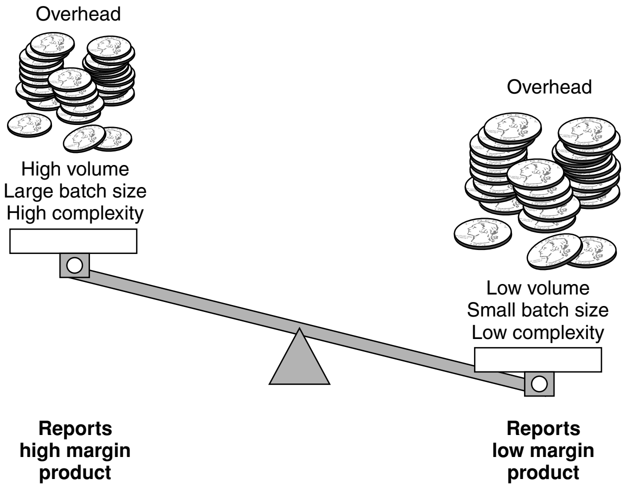

FIGURE 3.3.4 This is a schematic view of a partial ABC system and how it is developed. First, resources are identified from the general ledger. Then important activity centers such as purchasing and customer service are isolated. The method of allocating resources to the activity centers is calculated. Activity drivers are then determined to accurately reflect the direct (linear) relationship of each activity center to each product or service.

A demonstration of how fixed costs are assigned to a product is shown in the identification of *setup* and *engineering change* activities. Setup and engineering change costs depend on the quantity of each. Cost allocators are found by determining how the product or service is consuming setups and engineering changes. Therefore, assigning setup and engineering change costs to the product or service simply means determining the total setup and engineering change costs, then dividing each cost by the number of setups and engineering changes to determine the cost per unit. A product or service requiring two setups receives two units of setup costs, one requiring three setups would get three units, and so on. By identifying all activities and determining how each activity is consumed in the production of the product and service, all indirect costs can be identified directly.

COST ACCOUNTING AND ACTIVITY-BASED COSTING

BENEFITS OF ABC SYSTEMS TO THE ORGANIZATION

Reveals the True Cost

ABC systems benefit organizations in a number of ways. Such systems provide managers with a true cost of strategic choices so that they do not have to rely on intuition. By segregating costs according to activities, managers are able to approach cost reduction sensibly through cause and effect analysis. They are able to determine which are value- and non-value-added activities, perhaps for the first time. Thus, by focusing on the reduction of non-value-added activities, cost can be reduced without harming the long-term objectives of the firm.

Improves Decision Making

Understanding the links (drivers) between resources and activities and, in turn, the activities producing the product or service will help managers make product decisions even without dollar figures. ABC focuses on product and process simplification to facilitate continued cost improvements and increased competitiveness. No longer will cost distortion lead to incorrect decisions on product additions or abandonment, as has been the case for many organizations.

Clarifies Strategic Options

Managers using the information provided by the ABC system can review a range of strategic options. They can now identify the truly unprofitable products and decide which steps should be taken. Is it in the best interests of the organization to abandon the product? Should prices be raised? Low-volume products and services tend to have much more price elasticity than high-volume items, which may allow pricing for a profit. By using ABC systems to shift indirect cost away from high-volume products or services, a manager will have the option of lowering prices on products to increase market share. One of the most cost-effective ways to gain market share is by changing product mix. ABC develops the appropriate information to determine the best mix of products and/or services.

Provides a Means to Evaluate Technology

ABC systems provide a tool to evaluate new process technologies by focusing on the benefits of lowering material handling, improving quality to reduce inspections, reducing setups, improving process flow, and streamlining plant layout. Such costs can be readily identified on a product and product-line basis, so adjustments in efficiencies can be made.

Encourages Product Redesign

Good managers are constantly encouraging their design engineers to modify products to use fewer components and to ease manufacturing cost. However, most organizations do not have a system in place that traces the benefits of doing so in concrete terms. The information supplied by an ABC system encourages this process by showing the cost and benefits of meeting this objective product by product. Every manager in the firm will understand the cost and benefit of designing for manufacturability.

Eliminates Traditional Standards

ABC systems do not rely on traditional fixed standards. Instead, they use rolling standards, which continually compare prior periods with current periods. This promotes continued improvement and eliminates the need to try to keep traditional standards current. The focus of such a system is not whether the standard or actual cost is right, but whether it is getting better. Thus, the variances are used to improve the process—not to balance the ledger as traditional systems do.

Is Highly Motivational

The use of the ABC system provides a highly efficient means to modify the entire organizational process. Just as important, it provides the method to judge how changes in the performance of activities affect overall cost. The ABC system not only provides a highly accurate method of costing, but also promotes activity efficiencies by exposing activities that were once buried in an overhead pool. By separating the cost of these support activities, each department can directly trace the effect of its efficiencies on total product cost. Coupled with a responsibility accounting system, this information is highly motivational, since engineering can see the cost impact of its designs, purchasing will understand the impact of reducing or expanding vendors, and so on.

ABC IN ACTION

How ABC Systems Work

A good way to understand the application of ABC and ABM is to work through an actual example to compare information outputs between cost systems. In our comparison, we use the New England China Company, a fictitious manufacturing company. It produces a full line of china, including dishes. This manufacturer has a diverse product line with over 1000 patterns.

Although production volumes vary, direct labor and materials per unit are the same for each pattern. Volumes range from 10,000 to 120,000; however, total setups equal 25 regardless of production volumes. Variable overhead is $20,000, and fixed overhead is $80,000.

Using the data in Table 3.3.1, a profit and loss (P&L) statement can be constructed to show the effect of absorption-based costing, direct costing, and activity-based costing on margins. To keep this example simple, selling and general and administrative (G&A) expenses have been eliminated from the P&L, and indirect cost is just setup cost.

TABLE 3.3.1 Assumptions for the New England China Company P&L Statements*

	Blue	Floral	Gold	Total
Selling price	$1.75	$2.00	$2.20	
Unit volume	120,000	60,000	10,000	190,000
Product/volume %	63.2%	31.6%	5.3%	
Direct labor/unit	$0.40	$0.40	$0.40	
Material/unit	$0.60	$0.60	$0.60	
Average run quantity	4,800	2,400	400	7,600
Total number of setups	25	25	25	75
Variable overhead				$20,000
Fixed overhead				$80,000

* These assumptions are used to construct the P&L statements in Figs. 3.2 through 3.4. The New England China Company is a manufacturer of a full line of china products. In this example, three dish styles are shown: blue, floral, and gold patterns.

Table 3.3.2 shows the *absorption-based* P&L for the New England China Company. Sales are determined by multiplying unit selling prices ($1.75, $2.00, $2.20) by unit volume (120,000, 60,000, 10,000). Direct labor and material costs are calculated by multiplying the respective unit costs ($0.40 and $0.60) by the unit volume. Factory overhead was calculated by multiplying production volumes (63.16 percent, 31.58 percent, 5.26 percent) times the total overhead (O/H) of $100,000 (variable O/H $20,000 + fixed O/H $80,000 = $100,000). The resulting total expense was subtracted from sales to provide the gross margins, with a margin variance of 12.78 and 30.62 percent between the blue and gold patterns.

TABLE 3.3.2 Absorption-Based P&L for the New England China Company*

	Blue	Floral	Gold
Sales $	$210,000	$120,000	$22,000
Direct labor	48,000	24,000	4,000
Direct material	72,000	36,000	6,000
Factory overhead	63,158	31,579	5,263
Total expense	$183,158	$91,579	$15,263
Gross margin	$26,842	$28,421	$6,737
Gross margin %	12.78%	23.68%	30.62%

* This is a simplified P&L statement showing the effect of absorption-based costing for a high-, medium-, and low-volume product. Notice how the major portion of the factory overhead is applied to the blue-pattern dishes. That is because overhead is allocated based on a percentage of direct labor. Therefore, as units of production increase, so does the allocated overhead to that product.

This margin information indicates that the gold-pattern plates are almost 2.5 times more profitable than the blue-pattern plates. Management may now conclude that production of the blue plates should be reduced and production of gold plates with the greater margin should be increased.

In an uncomplicated example like this one, it can be seen that although the numbers report one set of circumstances, common sense may indicate the opposite is true. If the blue-pattern plates were reduced or eliminated, the cost would be shifted to the gold-pattern product with disastrous results. In a real-world environment, with more product lines and more complex variables, common sense may not be sufficient to slice through the information fog created by these misapplications. In that case, management may be caught making decisions based on incorrect or misleading information—perhaps eliminating a profitable product or product line altogether.

Changing from Absorption-Based to Direct Costing

The New England China Company decided to revamp its full-absorption costing system by implementing a direct-costing system known as *marginal income* (MI) so that distortions caused by the arbitrary allocation of overhead would be reduced. Table 3.3.3 shows the effect of this change. The first three lines of the P&L statement are identical to the absorption-based P&L statement. Line 4, the application of overhead, is the only difference. The variable overhead of $20,000 is applied to each product based on the proportionate amount of direct labor used for the production of each pattern. The resulting margins do not contain the large differences seen in Table 3.3.2. Instead, they appear more equal, even though the blue-pattern plate still appears to show the lowest profit margin and the gold pattern appears to be the most profitable.

TABLE 3.3.3 Marginal Income-Based P&L for the New England China Company*

	Blue	Floral	Gold
Sales $	$210,000	$120,000	$22,000
Direct labor	48,000	24,000	4,000
Direct material	72,000	36,000	6,000
Factory overhead	12,632	6,316	1,053
Total expense	$132,632	$66,316	$11,053
Gross margin	$77,368	$53,684	$10,947
Gross margin %	36.84%	44.74%	49.76%

* The use of marginal income costing allows the removal of fixed overhead cost from the overhead equation. This has the effect of equalizing margins so that only unit-based costs are considered. These are costs that directly relate to production. Variable overheads are still allocated on the basis of a unit of production (for example, labor-hours), rather than on the activity that originates the cost. However, the marginal income method still does not eliminate cost distortions, which arise from the arbitrary allocation process.

Yet management might have good reason to suspect these numbers, too. The initial reaction is that it doesn't appear to make economic sense that the lowest-volume product should have the highest margin, when we know that all direct costs are equal. Overhead, though much less of it, is still being arbitrarily allocated instead of applied to the product that actually caused the cost. The problem is that the remaining indirect costs are unassigned, so only partial product costs are seen. If those remaining costs could be assigned directly to the product based on how the product actually consumed them, management would have the truest product cost possible.

The Effect of Replacing Direct Costing with Activity-Based Costing

Table 3.3.4 demonstrates the implementation of such a solution—an activity-based costing system. Lines 1 through 4 are identical to Fig. 3.3.3. Line 5 has been added to show the effect of directly assigning indirect overhead to the product. In this case, the indirect cost is the setup cost. Since each of the three products has the same setup cost, it is an easy matter to assign one-third of this cost to each. The result is that the gold-pattern plates are being produced at a loss, whereas the blue-pattern plates (the highest volume) have the greatest margin.

TABLE 3.3.4 ABC-Based P&L for the New England China Company*

	Blue	Floral	Gold
Sales $	$210,000	$120,000	$22,000
Direct labor	48,000	24,000	4,000
Direct material	72,000	36,000	6,000
Variable overhead	12,632	6,316	1,053
Activity-based overhead	26,667	26,667	26,667
Total expense	$159,299	$92,983	$37,720
Gross margin	$50,701	$27,017	$(15,720)
Gross margin %	24.14%	22.51%	(71.45)%

* Activity-based costing significantly changes the gross margin when compared with the P&L statement in Fig. 3.2. Costs are now directly applied to the dishes based on how they are actually incurred. This method, said to provide the true cost, applies overhead based on direct labor-hours or some other unit of production. Costs that are not volume-related, such as inspection, setup, and purchasing, are attached to those units of production that contain the highest number of direct labor-hours. This distorts costs by reporting high volume, large batch size, and/or high-complexity products or services as *low-margin* items. It has just the opposite effect on low volume, small batch size, and/or low unit complexity.

Though these are simplistic examples, consider the impact on a P&L when all overhead costs are correctly attributed to product or services. It is not unusual to find triple-digit gross margin differences between the current costing system and an ABC system.

DESIGNING THE ABC SYSTEM

Objectives

ABC management information systems are typically more complex than traditional systems. Careful planning is needed to maximize the benefits. No two organizations will have the same information needs, because their companies' cost drivers can be very diverse. However, every system has at least eight basic steps in common that should be included in the design objectives:

- Determine design criteria.
- Identify resource categories.
- Identify activities.
- Analyze and categorize activities.
- Establish activity centers.
- Determine cost pools within activity centers.
- Determine resource drivers.
- Determine activity drivers.

Determining Design Criteria

A number of important design choices should be made prior to attempting implementation of any ABC system. Four of the more important are included here. However, each organization will have different requirements, so use them as a guide. Careful consideration should be made to assure that the system would be designed to achieve both long- and short-term organization objectives. The four questions to be answered are as follows:

- What are the strategic goals of the organization?
- How precise should the system be?
- Should the initial design be simple or complex?
- Should there be a pilot project first?

Strategic Issues. A designer must never lose sight of the fact that all management information systems should be created to serve the long-term goals of the organization. Without knowing or understanding what the strategic goals are, a system design could be fatally flawed. The designer must understand what information is required for each goal in order to conduct the strategic mission. Having established this top layer of information needs, all subsequent information hierarchies will be much easier to identify.

Stand-Alone System. The question of whether to integrate the ABC system into the organization's current accounting system or to install it as a stand-alone system will depend on the objectives. There is no single correct answer, since there are advantages to both. Having two systems tends to create controversy regarding which system is correct. As the old saw goes, "A man with two watches will never know the correct time." More important, there is an extra cost attached to operating two databases instead of one. Information has to be rekeyed or downloaded into the new system, which could mean some data-collection delays or errors.

In spite of these disadvantages, many organizations have opted to run their ABC systems on a stand-alone network. The reason offered most often is that it does not require the approval of the auditors; thus it can be up and running in a much shorter period of time. An integrated system requires a number of external and internal approvals, which could seriously delay or, worse, prevent the installation of the system altogether. Stand-alone systems are now operational in a wide variety of applications with excellent results in spite of the drawbacks of dual-system operations.

The Precision Question. A number of issues must be decided regarding the precision provided by any cost system. With an ABC system, high precision is possible—but at a greater cost since there are many more variables to account for than in a traditional system. For that reason, precision may not be the primary objective. An ABC system does not have to be highly accurate to be highly effective. Since traditional systems have been *precisely* wrong for years, the ABC system that is *approximately* right will be a vast improvement.

To determine the amount of precision the organization can afford, a cost-benefit analysis is conducted during the initial design phase. The 80/20 rule has application here. That is, 20 percent of an organization's products or services probably account for 80 percent of its cost. Once this relationship is established within the organization, selected costs and activities are chosen so that by very precisely controlling 20 percent (or whatever the ratio may be) of the activities, 80 percent of the costs are controlled. Of course, this will vary widely from organization to organization, but the concept remains valid.

As was seen in earlier examples, many traditional margins have been wrong by a factor of 100 percent or more. Choosing a less precise method of costing (interviews versus work measurement is an example) for establishing activity-based cost systems with margin variances of 10 to 20 percent may be perfectly acceptable—and more cost effective.

The Complexity Factor The more activities that can be identified and the more cost drivers that can be related to these activities, the more precise the cost data will be. However, the system quickly becomes complicated, with a number of risks attendant to this design strategy. Cost is the most obvious. More important, users can be overwhelmed with excessive data, which would certainly discourage the use of the system over time. Ironically, the more data required for input, the higher the risk for error—precisely what system designers are seeking to avoid.

A compromise strategy may be to design a more complex system only in the early stages of the project. In doing so, the designers will be sure to discover all important activities and related allocators, which could be missed in a less comprehensive approach. Thus, by recognizing all the variables early in the design, a critical driver or activity has a much better chance of being caught prior to the implementation phase. Then, with the complex design completed, the designer has far more options. The system can be installed as designed, installed in phases over time, or installed in a simplified format. It is far better to pare down a design prior to installation than to regret having failed to include a crucial activity six months after installation.

HOW THE INDUSTRIAL ENGINEER CAN HELP

It is now up to the industrial engineer (IE) to lead the way until cost accountants can regroup. With the IE's education and understanding (of new technologies, of the need for informational changes, and of technology's impact on product costs), he or she is best equipped to make management aware of the dire need to update the organization's cost information systems.

This rapid growth of technology has left a void that needs to be filled. The IE is the ideal candidate to assume this new leadership role to integrate automation and new service delivery systems with the organization's information system. The output of a modern cost and control system isn't just dollars-and-cents statistics as in the old days; it includes important decision-making information such as machine hours, pounds, standards, variances, and other measures that have always been the responsibility of the IE. At this time, only the IE has the needed tools to assist in the modernizing of current costing systems—systems that have been harming domestic industry's ability to compete adequately.

Our old cost and control systems were designed around high-volume, lower-quality products and for improving quarterly earnings at the expense of long-term company benefits. Such systems stymie efforts to achieve continuous improvement. These old systems need replacement, and the prime candidate to lead this revolution is not the cost accountant but the IE.

The product of all cost and control systems is *change.* Who is better equipped to handle this mission than the IE trained in the techniques of systems measurement, analysis, and productivity improvement—and, most important, change? One of the significant emerging changes in cost system integration is activity-based management. This chapter has familiarized the IE with this latest approach to cost information systems and their application.

SUMMARY

The experiences of managers who have used ABC systems in a wide variety of manufacturing, administration, and service environments indicate that a properly designed ABC system provides a strategic and tactical advantage far superior to more traditional systems. Activity-based costing helps managers understand and eliminate complexity. It provides managers with true product costs and removes bad cost information from the management decision-making equation. Activity-based costing also helps managers understand the impact of sourcing decisions.

Activity-based costing can change the way managers determine the mix of their product line, price their products, and analyze the impact of new technology. The designer of an ABC system has the ability to choose cost drivers that can strongly influence behavior and are highly motivational. In addition, such a system will yield an inordinate amount of information that managers may choose to eliminate.

The challenge for system designers is to establish an ABC system that provides not only accurate product and service cost information but also information on activities that can be easily and correctly interpreted. ABC is a very useful control tool for any organization.

Through the use of rolling standards and the ability to control activities, ABM will be the management system of choice for those organizations wishing to compete in the global marketplace.

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BIOGRAPHY

Edmund J. McCormick, Jr., has served as chairman of McCormick & Company, an international consulting firm founded in 1946 that specializes in strategic planning, management consulting, financial advice, profitability studies, cost control, and training. A recognized specialist in strategic planning, turnaround, and business engineering, he is the author of numerous papers and articles on planning, securitization, budgeting, cost control, and profitability. McCormick has served on the board of directors of Room Plus, Inc., a retail furniture manufacturer whose securities are traded on The NASDAQ Small Cap, Market Watchdog Patrols, Inc. (now NetWolves Corporation), and Kirlin Holding Corp. (symbol: KILN). He is currently a director of Greenleaf Partners II, LLC, as well as a comanager of Greenleaf Capital Partners, LLC. Both are private investment funds.

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CHAPTER 3.4

PRODUCT COST ESTIMATING

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This chapter will discuss the basics of developing a cost estimate. The estimate could be for any type of new task in any type of organization, but this chapter primarily addresses how to determine manufacturing costs for a new product. Included are sections on terminology; methods for determining costs for labor, materials, and processing; and techniques for developing standards using parametric procedures. Several examples, some with figures and tables, are provided. The topics discussed here provide only an overview of some of the techniques used for developing cost estimates. Each organization should determine which estimating methods best suit its needs.

ESTIMATING: AN EVERYDAY, EVERYBODY PROBLEM

Cost estimating is a popular activity within engineering. Whether the professional person is called a cost estimator, cost engineer, cost analyst, labor estimator, or material planner, the emphasis remains the same. He or she is required to answer a familiar question: "How much will it cost?" Although the purposes that underlie this question vary, we find that businesses, government, and not-for-profit organizations desire timely and reliable measures for economic needs. It is the engineer who does the appraisal, analysis, forecasting, and compiling of a pro forma document that extends from the basic cost ingredients to the bottom line of an estimate. Using this evaluation, other management people make decisions regarding price, make versus buy, return on investment (ROI), or public fiscal-year budget. Thus, the engineer finds a future value that responds to a specified need.

This historical trail of development of cost estimating is intimately tied to industrial engineering. The original concept of a *labor standard* was seminal in the development of standard cost plans found widely throughout business. Formal cost estimating started to take root around 1900 since it was connected closely with the manufacturing and construction that began to flourish at that time. Cost estimating is a long-established job and an everyday occurrence for many engineers.

WHY ESTIMATES OF COST ARE MADE

Every size and type of organization needs to develop cost estimates to make intelligent decisions. Some organizations employ professionals whose primary function is developing cost estimates. But employees in most functional areas should understand good cost estimating techniques. With current engineering practices, teamwork philosophies, and total employee involvement, more people need cost estimating knowledge and skills. Cost estimating procedures must be performed quickly and accurately because of tough customer demands and global competition. The following list explains several types of cost estimates that organizations routinely make.

1. *New product cost.* When new product concepts or product changes are being considered, detailed estimates of cost are needed to help management make proper decisions. Detailed estimates include costs of material, processing of material, fabrication, assembly, labor, and purchased components. The processing, fabrication, and assembly costs include estimates for tooling, dies, fixtures, inspection instruments, and so forth. Costs for capital equipment, space, and facilities are also major estimate areas. If a decision is made to proceed with the new product, the estimate may likely become the budget for the project. This type of estimate should be extremely detailed and cover needs and costs from inception through the life cycle. Today, *product life* has been extended to include recycling and disposal of the product and its components. It is not uncommon for companies to first determine the market selling price and then work backward to determine how much cost can be absorbed by different areas of the company. Within each organizational area, costs must be constrained to the limits allowed.

2. *Make or buy.* Companies should consider whether to make components in-house or to purchase the components from outside vendors. Price is usually the deciding factor, but other elements can affect the final decision. For example, can production demand requirements be fulfilled? Can quality expectations be met? Can delivery schedules be met? Likewise, it might be better to use a vendor who has been producing similar parts for years and who has the expertise to produce better parts. It is always wise to develop estimates for comparison.

3. *Selling price determination.* These estimates can work two ways. First, estimates are used to determine selling price. The estimate establishes the cost to produce, market, and deliver. Then a profit margin can be attached to establish a selling price. To enter an existing market, the competitive selling price can be used to work backward to determine whether producing the product is appropriate.

4. *Equipment and technology acquisition.* Companies frequently make decisions about purchasing new equipment, software, or complete systems to replace or add to the present resources. Often this involves comparing alternatives that comprise new technology and/or changing from manual to automated procedures. Developing accurate cost estimates for new and unfamiliar areas is not easy.

5. *Cost control.* Some companies, especially job-shop-type organizations, use cost estimates as a form of cost control. Lot sizes vary and are usually small, and almost every job is different. For these and other reasons, job shops seldom develop work standards to help determine costs. If a management decision is made to proceed with the new product, the detailed estimate may likely become the budget for the project. These estimates should not be considered temporary work standards because the objective is to determine whether the job can be done more profitably and less expensively than the competition can do it.

6. *Temporary work standards.* Flow-shop companies producing products in high volume use estimates as temporary work standards. Hopefully, these temporary standards will be replaced as soon as possible with accurate time studies, work sampling, or predetermined time standards.

7. *Vendor quote checks.* Cost estimates are sometimes used to check vendor bid quotations on outsourced work. This estimate can be used to not only verify appropriate costs for outsourced work, but also as a part of the total product cost estimate.

MEASURES OF ECONOMIC WANT

The task facing the engineer is to provide a fact or number that represents the economic want of the design. A *want* is a value exchanged between competing and selfish interests. The price a consumer is willing to pay for an item stocked on the grocery shelf, a contractor-owner agreement on the bid value of a building project, and the fiscal-year budget value for a weapons system that the U.S. Department of Defense proposes and Congress accepts are typical examples of wants exchange.

REQUEST FOR ESTIMATE

It is not common practice for cost engineers to initiate a request for an estimate. The request is typically generated from sales and marketing sources. Another source is engineering design from a potential customer. A request for quotation (RFQ) or request for proposal (RFP) is received by engineering design or generated in sales or marketing. A customer usually does not communicate with cost engineers; usually external communication goes through another function before coming to the cost engineer. Therefore, a request for estimate (RFE) is generated internally after an RFQ, RFP, or production inquiry is received.

Information needed varies for each RFE, but there are general areas of information that every engineer needs. Some of these are status of the design, quantity and production rate expectations, quality specifications, legal requirements (including environmental impact), delivery requirements, and location. Information necessary to the nature of the design and that needed to make a complete and accurate estimate should be provided to the engineer. But it is the engineer's responsibility to request proper information to develop the estimate. As in all decision-making areas, the cost estimate can be no better than the quality and completeness of the data used to create it.

Sources of estimating information are both internal and external to the organization. If the product is going to be produced within the organization, the product estimation is probably internal. Project data, which usually involves capital types of designs, are typically external sources of information. Commercial data and published and private indexes are sources of external data.

Before starting an estimate, it is essential to understand analysis of the elements of cost. Analysis of labor, material, and overhead costs must be undertaken. Once again, the estimate will be no better than the quality and thoroughness of the analysis that precedes the calculations. It is also vital that timely, up-to-date information be used.

The internal elements of cost details making up the estimate are primarily obtained from the accounting department. Cost accounting is the function that collects actual cost data on the various internal elements needed to develop the estimate. The following list offers a brief description of the primary elements.

1. *Direct labor.* Direct labor is the labor expended to add value to the product, sometimes described as the cost related to individuals who touch the product. Process operators, assemblers, and inspectors are included in this area.
2. *Indirect labor.* Indirect labor supports direct labor. These people are essential to the operation of an organization, but they add no value to the product being produced. Material handlers, tool-room employees, shipping and receiving employees, and maintenance people are some in this category.

3. *Direct materials.* Direct materials consist of both manufactured and purchased components that are part of the product being produced.
4. *Indirect materials.* Indirect materials are necessary to manufacture, test, and ship the product. Indirect materials are not part of the finished product. Sand used to build a sand cast mold is an example of indirect material. There is a cost associated with indirect material, and in some situations the indirect material can be used over and over.
5. *Overhead.* This is an accounting term. Included in this category are salary and management costs. Also, overhead includes all costs not covered in the preceding categories. Elements such as machinery costs, shop and office supplies, and insurance are included in this area. Often, in developing estimates, overhead is expressed as a percent of direct labor cost. For information on allocating overhead costs, refer to Chap. 3.3.
6. *General and administrative.* Many companies list general and administrative (G&A) costs as part of overhead. Other companies list these elements separately. Usually G&A costs are added to the estimate in the form of a percentage factor developed in the organization. Included in this category are sales commissions and top-executive salaries. These costs are provided by the accounting department and not by the cost engineer.
7. *Profit.* Profit that must be obtained from the product must be included in the cost estimate. This margin above production cost is provided by the accounting department and by top management.

PRELIMINARY AND DETAILED METHODS

Many methods are used to make estimates. They range from techniques that are quick and crude, *preliminary estimates,* to the tedious and more accurate methods, *detailed estimates.* Regardless of the type of design, the methods used in estimating are similar. Preliminary methods are used in the formative stages of design. They are meant to be fast and are not expected to be as accurate as those used to prepare detailed estimates. Detailed methods, at the other extreme, are used to set prices, make competitive bids, or allow organizational decisions to be made regarding economic actions. As might be expected, detailed methods are much more quantitative, and an attempt is made to suppress arbitrary and judgmental factors.

Quantitative estimating is desirable because it tends to provide more accurate estimates than do nonquantitative methods. Quantitative estimating that uses mathematical formulas is called *parametric estimating.* Parametric estimating is sometimes referred to as *statistical modeling.* Although parametric estimating methods have been used for many years, they are becoming more widespread because calculation techniques and estimating procedures are now available in computer software. Several methods will be subsequently discussed. They are presented in order from preliminary to detailed methods, from nonquantitative to quantitative (i.e., parametric). When broadly defined, these methods can be used for the four types of designs discussed earlier.

Judgment and Conference Method

Judgment is an important part of any estimating process. In the absence of data, and when time is of the essence, guesstimates may be the only way to derive some cost components for an estimate. The engineer best suited for the task would be the person developing the cost estimate because he or she would have the experience, common sense, and knowledge of the design. Time, cost, and/or quantities with regard to minor or major line elements are chosen using the engineer's experience. The engineer must remain objective in properly measuring all the present and future factors that could affect costs. When possible, judgmental estimating should be done collectively.

If time and resources allow, the nonquantitative consensus method of estimating, called *conference estimating,* can be used. The more the pertinent the knowledge that can be obtained from various sources about a particular detail, the better the chance of the estimate being correct. In addition to cost information, it's wise to include savings potential, marginal revenue, and so forth. The conference method relies on the collective judgment of the differences between previously determined estimates and their associated relationships with the new designs being considered.

Conference estimating usually involves bringing together representatives from various departments to confer with the engineers in roundtable discussions. Together, these groups determine costs for those design aspects for which they have been given responsibility. These conference estimates might be limited to specific areas such as direct labor, materials, and processing equipment. Later, overhead, distribution, selling price, and profit are added using the organization's various values and formulas. These indirect costs can be added to the estimate later if access to specific organization costing data is restricted.

The conference method is not typically analytical, and verifiable facts are usually lacking. When using the conference method, proper group managing techniques should be applied to ensure that the decisions are group decisions and are developed properly in the group setting.

Unit Method

The unit method, or a variation of it, is the most widely used preliminary estimating tool. This method may also be known as the *order-of-magnitude method, lump-sum method, module estimating,* or *flat-rate method.* Individuals often use the unit estimating method to estimate costs for their private needs. For example, when estimating what a new home may cost to build, an estimate of cost per square foot can provide a good ballpark figure. If construction costs in a geographical area are generally valued at \$545 per square meter, then a family could calculate the rough cost of having a 275-square-meter house built (\$545 × 275 = \$149,875 estimated cost of the house). Some other examples of unit estimates are as follows:

- Cost of components per kilogram of casting
- Manufacturing cost per machine shop labor-hours
- Chemical plant cost per barrel of oil capacity

All of these examples for estimating are *per* something. The information for these types of estimates can be obtained from the Internet, technical literature, government, banks, data files of cost engineering or accounting, and the service providers.

Contributing to the popularity of unit estimating techniques is their ease of use. Consider the manufacturing machining operation of turning. Using similar parts routings, the total time for several jobs and many part types for a lathe can be compiled. Taking averages of length of cut and time to cut, and knowing the direct labor charge, a cost per unit of length (inches or centimeters) of cut can be determined.

Comparison Method

The comparison method is similar to the previously discussed unit method, the difference being that formal logic is applied. If an extremely difficult design is being estimated or part of the design has an unsolvable section, it is given an identifying name such as *design A.* A simpler design problem is then constructed so an estimate can be made. The simpler problem is given a title such as *design B.* The simpler design might be developed from creative and clever manipulations of the original, more difficult design. The simpler estimate may also include more relaxed technical constraints than the original problem. Facts already known about design *B* will help the engineer in developing an estimate for design *A*. The alternative design problem *B* must be selected to relate to the original design by the following inequality:

$$C_A(D_A) \le C_B(D_B) \tag{3.4.1}$$

C_A and C_B are the cost values of the estimate for designs *A* and *B,* respectively. Likewise, D_A and D_B are the designs for *A* and *B.* Obviously, estimates are better when *B* approximates *A* as closely as possible. The cost value C_A of the estimate should be something less than C_B. A conservative position may be taken initially, as can be construed from Eq. (3.4.1). It may be management's policy to estimate the cost a little high at the beginning. Once the detailed estimate of design *A* is thoroughly explored, it may be found that $C_A(D_A)$ is less than the original comparison estimate.

A comparison estimate can be developed where high and low bounds are placed on either side of the estimate for design *A.* If a similar design is known for, or approximately known for a design *C,* the preceding logic can be used to expand the comparison inequality to the following:

$$C_C(D_C) \le C_A(D_A) \le C_B(D_B) \tag{3.4.2}$$

The assumption is made that designs *B* and *C* satisfy the technical requirements, and they bond the economic estimate for design *A.*

In practice, many engineers use comparison logic to develop estimates. Standard cost plans can provide "similar to" approaches, and analogy plans and computer retrieval schemes use this technique.

Factor Method

The factor method is an important method used for project estimating. Methods such as ratio, percentage, and parameter are approximately the same. The factor method is an extension of the unit method discussed previously. The unit cost estimating method was limited to a single factor for calculating overall costs. A natural extension of the unit method achieves improved accuracy by using separate factors for different cost items. For example, the estimate for the house construction from the unit method could be enhanced by added factors for certain types of heating and cooling units, tiled or wood floors, landscaping costs, and so on. All the various unit costs can be summed to obtain a more accurate estimate than the unit method provides.

The equation takes the following form:

$$C = C_e + \sum f_i C_e (I + f_I) \tag{3.4.3}$$

where C = cost of design being evaluated
C_e = cost driver or subdesign used as base
f_i = factor for estimating instruments, structures, site clearing, and so forth
f_I = factor for estimating indirect expense such as engineering, contractor's profit, and contingencies
$i = 1, 2, \ldots n$ factor index

The general idea is that with C_e is chosen as the cost driver, as in the example, the house would be the cost driver. Where in a community it is desirable to build the house would be a contributing factor, as would the specific design chosen and the amount of land required. These factors can all be correlated, and then historical data, design parameters, and indexes can be consulted for factor estimate.

Cost and Time Estimating Relationships

Cost estimating relationships (CERs) and time estimating relationships (TERs) are mathematical or graphical models that estimate cost or time. CERs and TERs are formulated to give estimates in either final or line-item form for a cost estimate. Rule-of-thumb estimates are not to be confused with CERs and TERs, which are analytical methods.

Learning Curve. An excellent example of a CER and TER is the learning curve. There are two types of learning curves, *unit cost* and *average cumulative cost,* as follows:

$$T_U \quad \text{or} \quad T_{AC} = KN^S \tag{3.4.4}$$

where T_U = cost, time, or value per unit of production, such as dollars or labor-hours, required to produce the Nth unit
T_{AC} = average cumulative cost, time, or value of N units
N = unit number, 1, 2, 3, . . . N
K = constant or estimate for $N = 1$, dimensions compatible with T
S = slope parameter of the improvement rate, equal to log L/log 2, where L = learning as percent of time (S is negative)

For example, if learning improvement requires only 85 percent of the previous time, then S = log 0.85/log 2 = –0.2345. The learning curve theory is based on the percentage of time or cost to build a quantity when doubled from the known time or cost. For example, assuming an 85 percent learning curve and assuming it takes 10 hours to build the first unit, then doubling that quantity, which is 2, tells us it would only require 8.5 hours to build the second unit. Doubling the quantity again, we could estimate that it would require only 7.225 hours to build the fourth unit (85 percent of 8.5 hours).

Learning curves can have either the unit or the cumulative average line as the straight line when drawn on a log-log graph format. In one presentation, on log-log paper, the cumulative average line is straight and the unit line curves under from unit 1 to 10 or 20 units. From then on, the unit line parallels the cumulative line. The other presentation form allows the unit line to be straight when plotted on log-log paper, and the cumulative average line, though starting together with the unit line at unit 1, curves above the unit line, and at about unit 10 to 20 the two curves will run parallel. Either way is acceptable, but it is important for the engineer to understand and clarify for other readers of the estimate which presentation is being used. When estimating to build N units, the cumulative average time may be more meaningful. A company is more likely to want to know how much time it will take to build N units (N times the cumulative average time) than to know how long it will take to build the Nth unit. Table 3.4.1 shows calculations for an 85 percent learning curve. Both approaches are shown.

Different types of manufacturing areas (electronic manufacturers, shipbuilders, etc.) have general learning curve slopes that apply to them. Each company should gather historical data for various types of products to develop cost and time estimates for any size of production demand. With knowledge of these slopes or other learning experiences, the engineer determines the appropriate factor for the job being estimated.

Ostwald [1] is one source of information on the development and application of learning curves. Many cost estimating books and work measurement books give information on learning curve techniques. Chapters 17.5 and 17.13 amplify learning curve concepts.

Power Law and Sizing Model. Another application of the CER is in the power law techniques. The power law and sizing model is frequently used when estimating equipment or components as a lump sum. This concept is concerned with designs that vary in size but are similar in type. An example might be estimating the design of a new and larger electric motor. The cost to produce a 50-hp motor can be estimated from data for manufacturing a 25-hp motor, provided that both are similar in design. Anyone familiar with manufacturing cost or economies of scale would not necessarily expect the larger 50-hp motor to be twice the cost of the 25-hp motor. The power law and sizing model can be expressed as follows:

$$C = C_r\left(\frac{Q_C}{Q_r}\right)^m \tag{3.4.5}$$

TABLE 3.4.1 Sample Learning Theory Table for 85% for Two Methods of Learning, Unit and Average

		Learning Table (ϕ = 85%)			
N	T_U or T'_a	T_c	T_a	T'_c	T'_u
1	1.0000	1.0000	1.0000	1.0000	1.0000
2	0.8500	1.8500	0.9250	1.7000	0.7000
3	0.7729	2.6229	0.8743	2.3187	0.6187
4	0.7225	3.3454	0.8364	2.8900	0.5713
5	0.6857	4.0311	0.8062	3.4284	0.5384
6	0.6570	4.6881	0.7813	3.9419	0.5135
7	0.6337	5.3217	0.7602	4.4356	0.4937
8	0.6141	5.9358	0.7420	4.9130	0.4774
9	0.5974	6.5332	0.7259	5.3766	0.4636
10	0.5828	7.1161	0.7116	5.8282	0.4516
11	0.5699	7.6860	0.6987	6.2693	0.4411
12	0.5584	8.2444	0.6870	6.7012	0.4318
13	0.5480	8.7925	0.6763	7.1246	0.4235
14	0.5386	9.3311	0.6665	7.5405	0.4159
15	0.5300	9.8611	0.6574	7.9495	0.4090
16	0.5220	10.3831	0.6489	8.3521	0.4026
17	0.5146	10.8977	0.6410	8.7489	0.3968
18	0.5078	11.4055	0.6336	9.1402	0.3913
19	0.5014	11.9069	0.6267	9.5264	0.3863
20	0.4954	12.4023	0.6201	9.9079	0.3815
21	0.4898	12.8920	0.6139	10.2850	0.3771
22	0.4844	13.3765	0.6080	10.6579	0.3729
23	0.4794	13.8559	0.6024	11.0268	0.3689
24	0.4747	14.3306	0.5920	11.7536	0.3616
30	0.4505	17.0907	0.5697	13.5141	0.3462
40	0.4211	21.4252	0.5356	16.8435	0.3233
50	0.3996	25.5131	0.5103	19.9811	0.3066
100	0.3397	43.7539	0.4375	33.9680	0.2603
500	0.2329	151.4504	0.3029	116.4542	0.1783

where C = total cost sought for design size Q_c
C_r = known cost for a reference size Q_r
Q_C = design size expressed in engineering units
Q_r = reference design size expressed in engineering units
m = correlating exponent, $0 < m \leq 1$

An equation expressing unit cost C/Q_C can be used as follows:

$$\frac{C}{Q_C} = \left(\frac{C_r}{Q_r}\right)\left(\frac{Q_C}{Q_r}\right)^{m-1} \tag{3.4.6}$$

As total cost varies as the mth power of capacity, C/Q_C will vary as the $(m - 1)$ power of the capacity ratio. When $m = 1$, a linear relationship exists and the law of economy of scale is ignored. For chemical processing equipment, for example, m is frequently approximately 0.6 and is sometimes called the "sixth-tenth model." The units of Q are required to be consistent since it enters only as a ratio. For situations such as inflation and deflation, the model can be altered to consider price change. A change factor C_I is placed in the equation along with index factors I_C and I_r as follows:

$$C = C_r\left(\frac{Q_C}{Q_r}\right)^m\left(\frac{I_C}{I_r}\right) + C_1 \tag{3.4.7}$$

where C_1 is the constant unassociated cost.

For estimating projects, a CER that can be used is $C = KQ^m$, where K is a constant for a project such as a processing plant, a new computer system, or a highway bridge. The concept of economy of scale is derived from this CER, where capital cost per unit produced reduces as the plant size increases. The scale factor m is not constant for all project designs. General scale-up or scale-down by more than a factor of 10 should be avoided.

Multivariable CERs are also possible. For instance, where symbols have been previously supplied, an equation such as the following could be used:

$$C = KQ^mN^S \tag{3.4.8}$$

Probability and Statistics Techniques

A number of estimating methods are based on probability and statistics. Cost is usually treated as a single-point value under conditions of uncertainty. Engineers, knowing the weakness of information and techniques applied, recognize that there are probable errors in the developed estimates. Knowing that the cost determined while developing the estimate is a random variable, using probability to estimate is appropriate. In the realm of statistics, a random variable is a numerically valued function of the outcomes of a sample of data. Four probabilistic techniques will now be discussed.

Expected Value. When an engineer can assign a probability estimate to elements of uncertainty as represented by the economics of the design, the method of expected value can be applied. Nonnegative numerical weights associated with design elements are assigned in accordance with the likelihood of the event occurring. The probability of the occurrence must equal 1. The probabilities describe the likelihood that the predicted event will occur. The method incorporates the effect of risk on potential outcomes by means of a weighted average. Each outcome of an alternative is multiplied by the probability that the outcome will occur. The sum of the products for each alternative becomes the expected value. It is mathematically stated as follows:

$$C(i) = \sum_j p_j x_{ij} \tag{3.4.9}$$

where $C(i)$ = expected cost of the estimate for alternative I
p_j = probability that x takes on value x_j
x_{ij} = design event

The p_j represents the independent probabilities that their associative x_{ij} will occur with $\sum p_j = 1$. For example, it may be predicted that the cost of fuel for use in the design would be charged at the following discrete cost pattern: 20 percent probability that fuel will cost \$3.00 per gallon, 30 percent probability fuel will cost \$3.50 per gallon, and 50 percent probability fuel will cost \$3.75 per gallon. Multiplying the discrete probability rates times their related fuel costs and summing gives the expected cost of \$3.525 per gallon.

Percentile Method. Estimates reflecting uncertainty may be specified by three values representing the 10th, 50th, and 90th percentiles of an unstated probability distribution. The best value for an engineer to use is the 50th percentile. The 10th percentile cost is the best-case scenario and represents a 1 in 10 chance that the actual cost will be lower. The 90th percentile cost is the worst-case scenario and represents a 1 in 10 chance the cost will be greater. An example follows:

	Percentile			Difference	
Item	10th	50th	90th	(50 – 10)	(90 – 50)
1	\$25	\$33	\$44	\$8	\$11
2	9	13	15	4	2
3	3	4	7	1	3

These costs can be assumed to combine independently, that is, a low cost with a midrange cost with another low cost. After estimating, the 10th and 90th percentiles are expressed as differences from the 50th (or midvalue). The next steps are to square the differences and sum.

	(50 – 10)	Midvalue	(90 – 50)
	\$64	\$33	\$121
	16	13	4
	1	4	9
Total	81	50	134
Square root	9		11.58

Total estimate at 10th percentile = \$50 – 9 = \$41

Total estimate at 50th percentile = \$50

Total estimate at 90th percentile = \$50 + 11.58 = \$61.58

Sensitivity analysis can be applied to the percentile method in a simple way, as follows:

Item	Contribution to low uncertainty	Contribution to total cost	Contribution to high uncertainty
1	79% (64/81 × 100)	66% (33/50 × 100)	90.3% (121/134 × 100)
2	19.8% (16/81 × 100)	26% (13/50 × 100)	3% (4/134 × 100)
3	1.2% (1/81 × 100)	8% (4/50 × 100)	6.7% (9/134 × 100)

This simple sensitivity analysis will identify items to be monitored for possible cost reduction.

PERT-Based Beta Distribution. This method was developed for predicting the expected duration of projects and monitoring the progress of the project's activities. The full name is *program evaluation and review technique* (PERT). It is based on using the most likely cost estimate, the most optimistic estimate (lowest cost), and the most pessimistic estimate (highest cost). These estimates are assumed to correspond to the beta distribution, which can be symmetrical or skewed left or right. Using the three estimates, a mean and a variance for the cost element can be calculated as follows:

$$E(C_i) = \frac{L + 4M + H}{6} \tag{3.4.10}$$

$$\text{var}\ (C_i) = \left(\frac{(H - L)}{6}\right)^2 \tag{3.4.11}$$

where $E(C_i)$ = expected cost for element I
L = lowest cost, dollars (optimistic)
M = modal value of cost distribution, dollars (most likely cost)
H = highest cost, dollars (pessimistic)

If several elements are estimated using this method, and if their costs are assumed to be independent of each other and are summed together, the distribution of the total cost is approximately normal. This follows from the central limit theorem. Figure 3.4.1 illustrates the use of the PERT method. The example shows how to find the contingency effects for a project design. Several elements must be combined when making the estimate to satisfy the conditions of the central limit theorem.

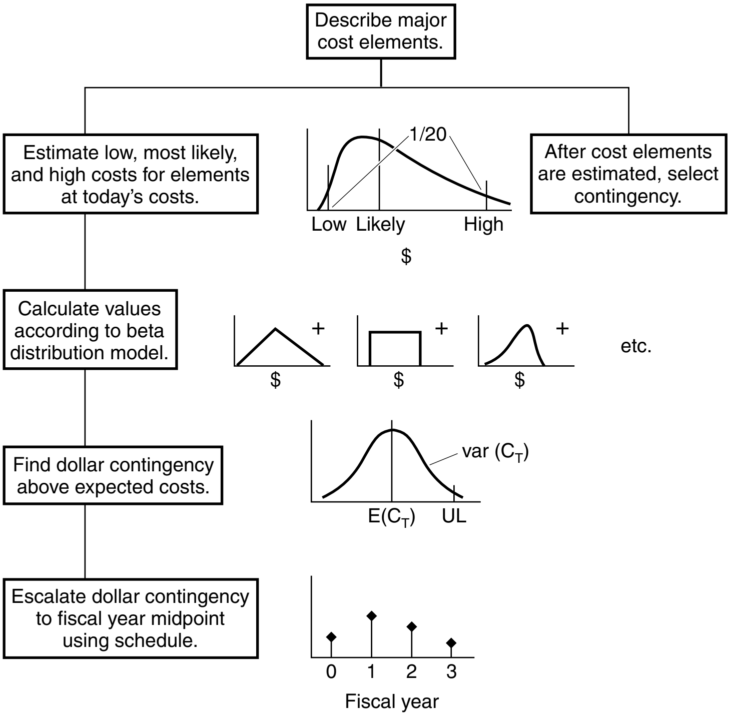

Describe major cost elements.
Estimate low, most likely, and high costs for elements at today's costs.
1/20
Low
Likely
High
$
After cost elements are estimated, select contingency.
Calculate values according to beta distribution model.
+
$
+
$
+
$
etc.
Find dollar contingency above expected costs.
var (C_T)
E(C_T)
UL
Escalate dollar contingency to fiscal year midpoint using schedule.
0
1
2
3
Fiscal year

FIGURE 3.4.1 Flowchart of PERT-based estimating.

$$E(C_T) = E(C_1) + E(C_2) + \ldots + E(C_n) \tag{3.4.12}$$

$$\text{var } (C_T) = \text{var } (C_1) + \text{var } (C_2) + \ldots + \text{var } (C_n) \tag{3.4.13}$$

where $E(C_T)$ represents the expected total cost in dollars and *var* (C_T) is the variance of total cost in dollars.

Computer Simulation. Simulation techniques are becoming more acceptable as tools for engineers developing costs of projects and systems. As computer simulation packages become more user-friendly and as computer memory gets larger and computation speeds become faster, simulation as a tool for estimating becomes more popular. *Simulation* is defined as the manipulation and observation of a synthetic (logical and mathematical) model representative of a real design that for technical or economic reasons is not susceptible to direct experimentation. The simulation model is developed to represent the essential characteristics of the real system with many minor details omitted. A computer is mandatory for this type of analysis. Product estimates are detailed and not suited for simulation techniques, although simulation could be applied to determine costs and times for manufacturing systems being estimated to produce the product.

Standard Data

Standard data are defined as standard time values for all manual work in an estimate. Standard data provide the opportunity to be consistent when developing an estimate.

The most accurate way to estimate direct labor cost is with standard time data developed from one of the formal time-measurement techniques (see Chap. 5.3). It is not the original time measurements that the engineer desires, but rather a set of engineering performance data or standard time data that are needed to make the estimate. Frequently, raw data or times for specific methods are incorrect because methods are altered, equipment is replaced, environmental conditions change, and so on. Industrial engineers may use regression analysis or other techniques to extend these raw data into a more usable form, such as standard data. It is easier to calculate standard time data for processes such as machining operations than for fabrication processes. Most of the work content in metal removing on a machine tool is fixed machine time. In fabrication, much of the time may be manual and subject to variation depending on individuals performing the work activities.

Standard time data may be divided into preliminary or detailed data. As with preliminary and detailed estimates, the engineer is more likely to be interested in preliminary standard data early in estimating; later, detailed data becomes more important. Standard time data are ordinarily determined from any of the various methods of observing work: time studies (see Chap. 17.2), work sampling (see Chap. 17.3), predetermined motion time standards, and historical data.

Time Study. Larger companies develop standard data from stopwatch time studies. Time studies are used to establish rates of production. When time studies are used to establish standard data, care must be taken in defining element content so work content can be isolated.

Predetermined Time Standards. Usually, one of the commercial systems like MTM or MOST (see Chap. 5.1, and Chap. 17.4) will be used, but sometimes companies will develop their own system. The main advantage of predetermined time standards is the consistency of the data. The major disadvantage is the amount of time necessary to develop the data. The major commercial systems are computerized, which allows for much faster development time.

Work Sampling. This technique of work measurement uses the fundamentals of probability and statistics to develop work standards by making random observations on jobs over a specific period of time. This method is widely used in white-collar environments. It is a desirable technique for studying team activities and also long-duration activities.

Historical Data. Past history or actual performance on jobs produced can be used to develop standard data. A disadvantage of this technique is that it rarely considers the best method of organizing work. This method is popular in smaller companies that do not have the resources to use other work measurement methods to develop standard time data.

In manufacturing, time study and predetermined motion time data are the major sources of standard data. In construction and white-collar environments, work sampling and labor-hour reports are the principal means of information. Likewise, in certain government agencies such as the post office and the military, work sampling and labor-hour methods are used.

Computer databases allow for easily and readily accessible time standard data. Often, hard-copy charts and tables are used, especially when the engineer is familiar with such estimating tools. Curves from figures and formulas are not recommended as a way of obtaining final expressions for standard time data because there is a tendency toward incorrect interpolation and because they are quite time-consuming to read or calculate and are subject to faulty execution and extension. Charts replace curves as the preferred final expression of standard time data. Charts and production information can be found in Ostwald [2]. When developed properly, standard time data is considered to be accurate and relatively inexpensive.

LABOR ANALYSIS

Labor constitutes one of the most important items of operation designs. Labor has received intensive study, and many recording, measuring, and controlling schemes have been developed in an effort to manage it. Labor can be classified in a number of ways, including direct-indirect, recurring-nonrecurring, designated-nondesignated, exempt-nonexempt, wage-salary, blue-collar–management, and union-nonunion. Other ways in which to classify labor are according to social, political, and educational divisions and type of work. Payment of wages may be based on attendance or performance. For cost-estimating operation designs, the direct-indirect classification is the most appropriate.

For operation designs there is an unquestioned dependence on the following simple qualitative formula:

$$\text{Labor cost} = \text{time} \times \text{wage} \tag{3.4.14}$$

The selection of time matches the requirements of the operation design. Time is expressed relative to a unit of measure, which is denoted in terms such as *piece, bag, bundle, container, unit,* or *board foot.* The usual ways to measure labor are by time study, predetermined motion-time systems, work sampling, and labor-hour reports.

Job tickets, especially for smaller organizations, are analyzed and allocated to units of work. For instance, a job ticket may read “136 units turned of part number 8641” and list “6 labor-hours.” Simple analysis would show 0.044 hr/unit. The engineer would use 0.044 hr the next time this part was run. Although hardly accurate because of the nature of historical work reports, labor-hour reports are used because of their simplicity. Labor-hour estimating data are especially popular in construction work.

Direct observation and measurement of labor are of little use to the engineer, except for guesstimates of similar work or reruns of the same work. Although the cost engineer may not be directly involved with the measurement of labor, he or she does depend on work measurement. The engineer is satisfied if such labor measurements are objective, as far as that is possible, and is willing to use the information provided that engineering techniques were used in the determination of time. Although the time measurements are of value, it is immensely more important that work measurement data be transformed into information that can be applied prior to the time of the operation design.

The time measurements are more valuable when expressed as standard time data (see Chap. 5.3) and presented in a table or computer format (see Chap. 5.6). The estimating data may be described in terms of elements, which are the subwork descriptors of operations, or may be expressed as time estimating relationships (TERs) for operations. Standard data expressed at the predetermined motion-time level are too detailed for much cost estimating work. But a typical TER is satisfactory for much cost estimating work. A typical TER for a drill press operation of sheet-metal parts is for setup of 0.2 + 0.05 per tool hour and for run time of 0.015 + 0.003 per tool + 0.001 per hole hour per unit. Thus, if a sheet-metal part requires two different countersinks for 22 holes, setup would be 0.3 hr and run time 0.043 hr per unit.

In some situations the estimate of time may be done from a guesstimate and therefore may be unrelated to measured, referenced, and analyzed data. A guesstimate is based on the engineer's observational experience. In some circumstances, these judgmental numbers are unavoidable.

The second part of Eq. (3.4.14), wage, is defined in the context of the operation design that is being estimated. The operation design may be for one worker and one machine, for a crew with one machine, or for a crew with several machines or processes. In the simplest case, one on one, the job description and job design (see Chap. 4.3) are specifications available to the engineer. The number used for the wage corresponds to the time period of work and is out-of-pocket money. Regression methods, labor contract, or personnel planning are sources for wage-trend information.

The practice of what to include in the wage amount is determined in conjunction with overhead. Fringe additions could include paid holidays and vacations, health insurance and retirement benefits, Federal Insurance Contributions Act (FICA) benefits, workers' compensation, bonuses, gifts, uniforms, special benefits, profit-sharing costs, education, and so on.

MATERIAL ANALYSIS

The term *direct materials* includes raw materials, purchased parts, standard commercial items, interdivisional transfers, and subcontracted items required for the design. Direct material cost is the cost of material used in the design. The cost should be significant enough to warrant the cost of estimating it as a direct cost. Some material costs, by virtue of the difficulty of computation and estimating, may be classified as either indirect or direct costs. The latter estimates are preferred. Paint for irregularly shaped objects is an example of material that can be classified either way.

The engineer begins by calculating the final exact quantity or shape required for a design. To this quantity, losses for scrap, waste, and shrinkage are added. The general model for cost of direct material is as follows:

$$S_a = S_t(I + L_1 + L_2 + L_3) \tag{3.4.15}$$

where S_a = actual shape in units of area, length, mass, volume, count, and so on
L_1 = loss due to scrap, decimal
L_2 = loss due to waste, decimal
L_3 = loss due to shrinkage, decimal

Scrap is material that is lost because of human mistakes, whereas *waste* is necessary because of the design. *Shrinkage* losses are due to theft or physical deterioration. In estimating of foodstuffs, if direct material is not processed at the appropriate time or if it is mishandled, shrinkage of the quantity will result. It is required that these three losses be estimated and that their percentages be added to the theoretical finished requirement.

An example of material estimating is given by the 355-ml (12-oz) beverage can, which is composed of the body, top, and pull ring. The container body, blanked from 3004 H19 aluminum coils, is shown in Figure 3.4.2. An intermediate cup is formed without any significant change in thickness. The cup is drawn in a horizontal drawing machine and squeezed to side-wall thickness of 0.140 mm (0.0055 in), while bottom thickness remains unchanged. The can is trimmed to final height to give an even edge for later rolling to the lid. Various mensuration formulas are used to find first the volume and weight of the object. This eventually relates to the amount of coil aluminum stock.

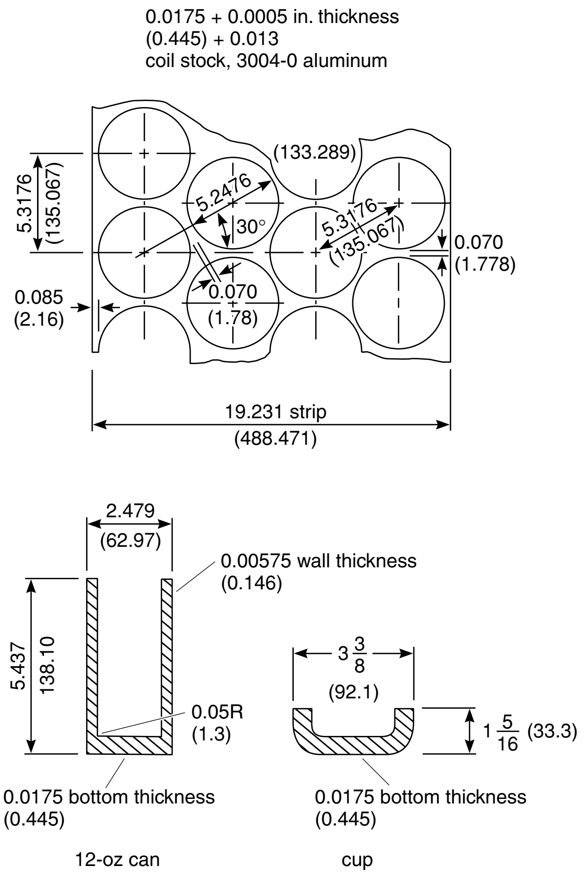

0.0175 + 0.0005 in. thickness
(0.445) + 0.013
coil stock, 3004-0 aluminum
5.3176
(135.067)
(133.289)
5.2476
30°
5.3176
(135.067)
0.070
(1.778)
0.085
(2.16)
0.070
(1.78)
19.231 strip
(488.471)
2.479
(62.97)
0.00575 wall thickness
(0.146)
5.437
138.10
0.05R
(1.3)
$3\frac{3}{8}$
(92.1)
$1\frac{5}{16}$ (33.3)
0.0175 bottom thickness
(0.445)
0.0175 bottom thickness
(0.445)
12-oz can
cup

FIGURE 3.4.2 Simple design for a beverage container: the common 12-oz can.

NEED FOR ACCOUNTING DATA

Cost accounting has always been important to the performance of diverse estimating functions. As colleagues in the gathering, analysis, and reporting of business data, accountants provide overhead rates, standard costs, and budgeting data. The engineer reciprocates with labor and material estimates for the several designs. In many situations, the estimate can serve as a mini profit and loss statement for special products. Thus, there is interdependence between these two professions. The engineer is less interested in balance sheets, profit and loss statements, and the intimate details of the structure of accounts. Overhead rates are vital for the estimating functions, however, since the engineer may apply these rates in the estimate.

By definition, *overhead methods* would include the following:

- Whether the rate includes fixed costs (as in absorption costing) or not (as in direct costing)
- The base used to distribute overhead, such as direct labor dollars, direct labor-hours, or machine hours
- The scope of the application of the rate, whether for the plant, cost center, machine, or design
- Whether the rate applies to all designs (such as product lines) or to one line of the design

FORECASTING

Many forecasting techniques have been developed to handle a variety of problems. Each has its special advantage, and care is necessary in choosing techniques for cost estimating. Selection of a method depends on the context of the forecast, availability of historical data, accuracy desired, time period to be forecast, and value to the company. The engineer should adopt a technique that makes the best use of the data. He or she should initially use the simplest technique and not expect more from the advanced technique than is justified.

For estimating requirements, we are concerned with data about labor, material overhead, and their quantities and cost. The forecast should reflect those values under the proposed actions of the company and environment. It is necessary to recall that forecasting is a future prediction about line elements of the estimate. Forecasts should not deal in overall or grand average cost, time, and quantities, but should be matched to line items required by the pro forma estimate. Forecasting is not estimating as the terms are used here, since forecasting takes data and frames it in a new picture, and judgment is suppressed as much as possible.

INDEXES

Cost estimating indexes are useful for a variety of purposes. Principally, they are multipliers to update an old cost to a new cost. Some examples of indexes are material, labor, material and labor, regional effects, and design type. Where C is the reference cost associated with a reference index I_r, it is linked in terms of time to the index I.

$$C = C_r\left(\frac{I}{I_r}\right) \tag{3.4.16}$$

Indexes are prepared and published by the government, private industry, banks, consultants, associations, and trade magazines. It is important to determine one's own indexes, especially for materials or labor not charted by other groups.

A cost index is meaningful only in that it expresses a change in price level between two specific times. A cost index for steel in 2001 alone is meaningless. An index for material A has no relationship to the index for material B. Similarly, the cost indexes for material A in two geographical areas may not be directly comparable.

To compute a price index for a single material, a series of prices must be gathered covering a period for a specific quantity and quality of that material. Index numbers are usually computed on a periodic basis. The federal government gathers data and calculates and divulges index numbers for periods as short as a month. The prices gathered for the material may be average for the period (month, quarter, half year, or year) or may be a single observed value as found on invoice records for one purchase.

Assume that the following prices have been collected for a standardized unit of silicon laser glass material:

Period	0	1	2	3	4	5
Price	\$43.75	\$44.25	\$45.00	\$46.10	\$47.15	\$49.25
Index, %	94.9	96.0	97.6	100.0	102.3	106.8

Index numbers are computed by relating each period price to one of the prices that has been selected as the base. If period 3 is the benchmark period, because the index is 100, or 1, period 2 price divided by period 3 price = \$45.00/\$46.10 = \$0.976. When period 3 price is expressed as 100.0, period 2 price can be expressed as 97.6.

Movements of indexes from one period to another are expressed as percent changes rather than as changes in index points. Period 6, 7, and so on can be projected, and if a reference price is known, a future price can be calculated. For instance, if $C_2 = \$3700$, then we can project that $C_7 = \$3700 \times (110.0/97.6) = \$4170$.

Assume that a product called "10-cm disk aperture laser amplifier" is selected for a composite index. Although the 10-cm disk amplifier was produced only during period 0, tracing of selected cost items has continued. To worry about all amplifier components is too involved, so major items were picked for individual tracking and spot prices gathered for four years. The quantity of each of the five materials is in proportion to the initial one-time cost of the material to the total cost. Some materials have declined in price, whereas others have increased. Prices for each material have been gathered (or inferred for periods where no information was available) and are shown in Table 3.4.2.

TABLE 3.4.2 Simple Calculation of Index for Composite of Several Materials

Calculation of index for material, quantity, and quality specifications						
Specification			Period			
Material	Quantity	Quality	1	2	3	4
1. Laser	3–10–cm disk	Silicate	$26,117	$27,027	$22,345	$21,228
2. Stainless steel turnings	18 kg	AISI 304	$1,913	$2,008	$2,129	$2,278
3. Aluminum extrusion	4 kg	3004	$418	$426	$439	$456
4. Fittings	3 kg	MIL STD 713	$637	$643	$656	$657
5. Harness cable	4 braid, 4 m	MIL STD 503	$2,103	$2,124	$2,134	$2,305
6. Annular glass tube	12 m	Tempered 3/16-in wall PPG-27	$4,317	$4,187	$4,103	$4,185
Total			$35,505	$33,415	$31,806	$31,109
Index (%)			100	94.1	89.6	87.6

The prices conform to quantity and quality specifications. With the index at 100 for benchmark period 0, the following indexes are calculated as 94.1, 89.6, and 93.3. If the unit cost is $43,650 during period 0, the estimated cost is equal to $37,953 at period 5.

One may argue that cost facts, materials, quantities, and qualities are not consistent as given in Table 3.4.2. Indeed, if technology is active, a decline in the cost and index is possible. Indexes should reflect basic price movements alone. Index creep results from changes in quality, quantity, and the mix of materials or labor. Table 3.4.2 is an example of a product index. The components in this case are selected on the basis of their contribution to the product value. Selection of components could be 100 percent, random, or stratified in accordance with the needs of cost estimating. Quantity is determined proportional to the design requirements. Specifications provided by engineering are used to fix quality characteristics. Product indexes can be maintained by noting the changes when they occur, inputting all previous data, and recalculating the previous year's indexes. Every so often it may be necessary to reset the benchmark year whenever delicate effects are influencing the index and are not being removed.

OPERATIONS ESTIMATING FOR MANUFACTURING

Operations Sheet

The operations sheet is fundamental to manufacturing estimating. It is also called *route sheet, traveler,* or *planner.* There are many styles, and each plant has its own form. The purpose of the operations sheet, however, is the same:

- To select the machine, process, or bench that is necessary for converting the material into other forms
- To provide a description of the operations and tools
- To indicate the time for the operation

The order of the operations is special, too, as this sequence indicates the various steps in the manufacturing conversion.

Each operations sheet has a title block indicating the material part number, date, quantity, engineer, and other information that may be essential to the company. Following the writing of this information on the form or its entry into the computer, the instructions to the plant are provided.

Suppose that we want to machine an aluminum casting that is on material consignment (meaning that the material is being supplied at no transfer cost). The casting is called SOHO and the part number is unknown. This casting is a consignment material and is part of a larger product. This casting will have a bored hole enlarged and deburred, and it will be packaged in a carton. Now your parts and assemblies are more complicated than this, but we only want to identify the process of estimating. A typical simple operations sheet would appear as shown in Fig. 3.4.3. A company's data warehouse for manufacturing estimating is used to supplement the estimating forms. These data are typical of a company's database that would allow the entry of information.

Preparing the Operations Sheet

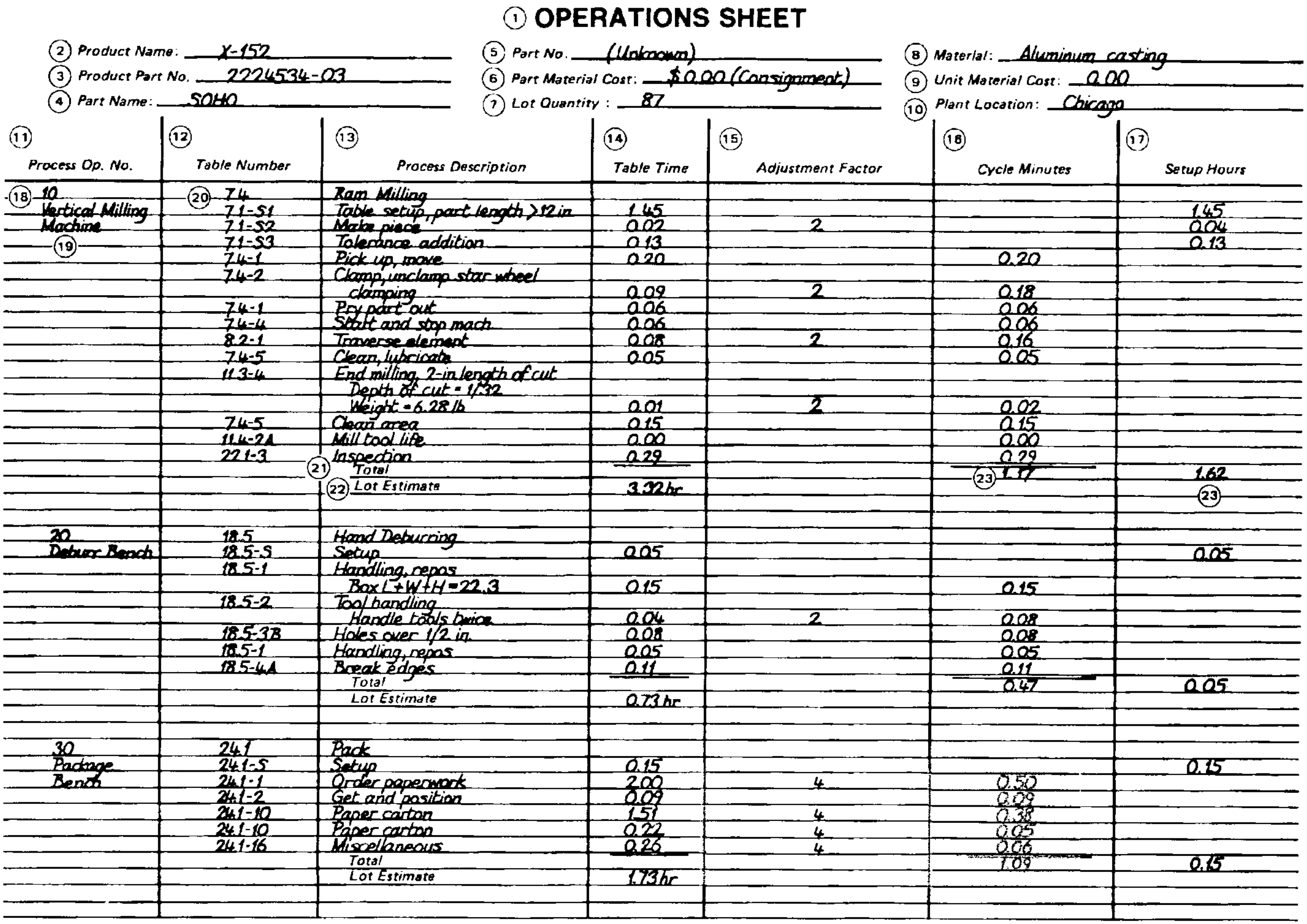
The operations sheet (1) begins in the upper left-hand corner of Fig. 3.4.3. The final product name (2) is often given along with the assembled product (3). The operations sheet is for a specific part name (4), which in this case is SOHO. A part number (5) can be identified and listed if available. The part number and name are removed from the design and repeated on the operations sheet title block. The engineer will write lot quantity (7) and material specification (8). Knowing the final amount of material required by the design, the engineer will add material to cover losses for scrap, waste, and shrinkage and multiply by the cost per pound of the material. Material cost, using the formula given earlier, is used to enter the value. A unit material cost is required for entry (9).

The sequence of the operation number and selection of the machine, process, or bench are made to manufacture the part. These are required at circle 10 and are shown specifically at (18) and (19). A complete operations sheet will show this column. Even though they are vital in operations planning, their importance is less in detailed estimating once that operation has been selected.

The column titled "Table Number" (12) corresponds to the table number indicated by the database AM Cost Estimator (2). For example, "Table 7-4" refers to the Ram Milling Machine class. The operations sheet column titled "Process Description" (13) consists of instructions to the shop that they will follow in making the part or subassembly. Shop instructions for operation number 10 are listed in Fig. 3.4.3.

The process description column lists the elements of the operation. These correspond to the element description listed in the estimating tables. It is an elaboration of the description given in the operations planning sheet described earlier; there is no basic difference, except that the number of lines or elements are greater for estimating than for planning. The process description may also indicate additional information such as length of cut, tooling used, type of NC manuscript order, and so forth.

The "Table Time" column (14) is a listing of the values removed from the estimating tables. A company will have developed estimating tables, and this information will have some numbering system to allow backtracking for later verification or adjustment. These time values are posted in this column.



① OPERATIONS SHEET

② Product Name: X-152
③ Product Part No. 2224534-03
④ Part Name: SOHO
⑤ Part No. (Unknown)
⑥ Part Material Cost: $0.00 (Consignment)
⑦ Lot Quantity: 87
⑧ Material: Aluminum casting
⑨ Unit Material Cost: 0.00
⑩ Plant Location: Chicago

⑪ Process Op. No.	⑫ Table Number	⑬ Process Description	⑭ Table Time	⑮ Adjustment Factor	⑯ Cycle Minutes	⑰ Setup Hours
⑱ 10	⑳ 7.4	Ram Milling				
Vertical Milling	7.1-S1	Table setup, part length >12 in	1.45			1.45
Machine	7.1-S2	Make piece	0.02	2		0.04
⑲	7.1-S3	Tolerance addition	0.13			0.13
	7.4-1	Pick up, move	0.20		0.20	
	7.4-2	Clamp, unclamp star wheel				
		clamping	0.09	2	0.18	
	7.4-1	Pry part out	0.06		0.06	
	7.4-4	Start and stop mach	0.06		0.06	
	8.2-1	Traverse element	0.08	2	0.16	
	7.4-5	Clean, lubricate	0.05		0.05	
	11.3-4	End milling, 2-in length of cut				
		Depth of cut = 1/32				
		Weight = 6.28 lb	0.01	2	0.02	
	7.4-5	Clean area	0.15		0.15	
	11.4-2A	Mill tool life	0.00		0.00	
	22.1-3	Inspection	0.29		0.29	
		㉑ Total			㉓ 1.17	1.62
		㉒ Lot Estimate	3.32 hr			㉓
20	18.5	Hand Deburring				
Deburr Bench	18.5-S	Setup	0.05			0.05
	18.5-1	Handling, repos				
		Box L+W+H = 22.3	0.15		0.15	
	18.5-2	Tool handling				
		Handle tools twice	0.04	2	0.08	
	18.5-3B	Holes over 1/2 in.	0.08		0.08	
	18.5-1	Handling, repos	0.05		0.05	
	18.5-4A	Break edges	0.11		0.11	
		Total			0.47	0.05
		Lot Estimate	0.73 hr			
30	24.1	Pack				
Package	24.1-S	Setup	0.15			0.15
Bench	24.1-1	Order paperwork	2.00	4	0.50	
	24.1-2	Get and position	0.09		0.09	
	24.1-10	Paper carton	1.51	4	0.38	
	24.1-10	Paper carton	0.22	4	0.05	
	24.1-16	Miscellaneous	0.26	4	0.06	
		Total			1.09	0.15
		Lot Estimate	1.73 hr			

FIGURE 3.4.3 Example of process sheet with balloons for instruction sequence.

The table time column identifies the estimating table and element number. For example, if a sheet-metal operation of braking were necessary, the number 3.6 would be first posted. Similarly, for a drill press operation, 9.3 would be written on the row corresponding to the machine selection. Notice that for any estimating table, clusters of elements have a number, too, starting with 1, 2, and so on. These clusters are generally related. The element "handle" may have many possibilities and be listed as element 1. Following the machine number, we list the element number, preceded by a dash. For example, 3.6-1 is a power press brake element called "brake." Also, 9.3-2 is a cluster of elements for "clamp and unclamp" for the upright drilling machine.

Adjustment Factor Column. The "Adjustment Factor" (15) column operates on the time column. Once adjusted, the time is either entered into the "Cycle Minutes" (16) or the "Setup Hours" (17) column. There is more discussion on the adjustment factor column later.

The cycle minutes and setup hours columns are very important, and the instructions that follow describe the methods and selection of the elements and time necessary to manufacture the part for that operation.

The sequence number (18) of the operation is given in the left-hand column along with the equipment (19) necessary for the operation.

The total (21) of the cycle minutes column and the total (22) of the setup hours column are summed. The lot estimate is calculated and presented (23), with the dimensions in hours. "Lot estimate" is a computation that is shown on the operations sheet. The calculation is made using the setup, unit estimate, and the lot quantity.

This operations sheet can be altered to consider simple assemblies or complicated products, but the approach remains the same. The purpose of estimating is to provide time or cost for the direct labor or material component of the product. The preparation of the operations sheet is important for the finding of part operational costs. Notice that the part cost is the sum of the operational costs, and this fact allows us to concentrate on the important steps that are necessary for estimating operations. Once the operational sequence, the selection of the machine, process, or bench, and a basic description of the work have been roughed out, cost estimating begins.

Setup Hours Column. Setup includes work to prepare the machine, process, or bench for product parts or the cycle. Starting with the machine, process, or bench in a neutral condition, setup includes punch in/out, paperwork, obtaining tools, positioning unprocessed materials nearby, adjusting, and inspecting. It also includes return tooling, cleanup, and teardown of the machine, process, or bench to a neutral condition ready for the next job. Unless otherwise specified, the setup does not include the time to make parts or perform the repetitive cycle. If scrap is anticipated as a consequence of setup, the engineer may optionally increase the time allotment for unproductive material.

Setup estimating is necessary for job shops and companies whose parts or products have a small to moderate quantity of production. As production quantity increases, the effect of the setup value lessens its prorated unit importance, although its absolute value remains unchanged. Setup values may not be estimated for some very large quantity estimating. In these instances setup is handled through overhead practices. Our recommendation is to estimate setup and to allocate it to the operation because it is a more accurate practice than costing by overhead methods. This recommendation applies equally to companies manufacturing their own parts or products and vendors bidding for contract work.

Some operations, such as flexible manufacturing systems, continuous production, or combined operations, may not require setup time. Nonetheless, even a modest quantity may be appropriate in these circumstances. Discussion of the details regarding setup is given for each machine, process, or bench.

Cycle Minutes. Cycle time, or run time, is the work needed to complete one unit after the setup work is concluded. It does not include any element involved in setup. Besides finding a value for the operational setup, the engineer finds a unit estimate for the work from the listed elements, which is called *estimating minutes.* This term implies a national norm for trained workers. These times include allowances, in addition to the work time, that take into account personal requirements, fatigue (if the work effort is excessive due to job conditions and environment), and legitimate delays for operation related interruptions. Since the allowances are included in the time for the described elements and therefore part of the allowed time for several elements (and hence several or many operations), then the allowed time is fair. The concept of fairness implies that a worker can generally perform the work throughout the day.

PRODUCT ESTIMATING

The cost summary (24) is for the part SOHO, and the header information is repeated (see Fig. 3.4.4). It is an important principle of this author that estimating for manufacturing requires that each operation be estimated. Each operation (18) is identified, and these correspond to the basic operations sheet. The cost engineer table number (12) identifies the basic data set for that operation. Balloon (25) specifies the description of the machine, process, or bench necessary to perform the operation. Lot hours (28) are transferred from the operations sheet. These lot hours differentiate between quantity. For low quantity, the setup becomes more important, whereas the cycle minute influences the lot hours if the quantity is large. Whether the part is for small or large quantity, the method is acceptable. The system is acceptable even with very large quantities that mechanization would require.

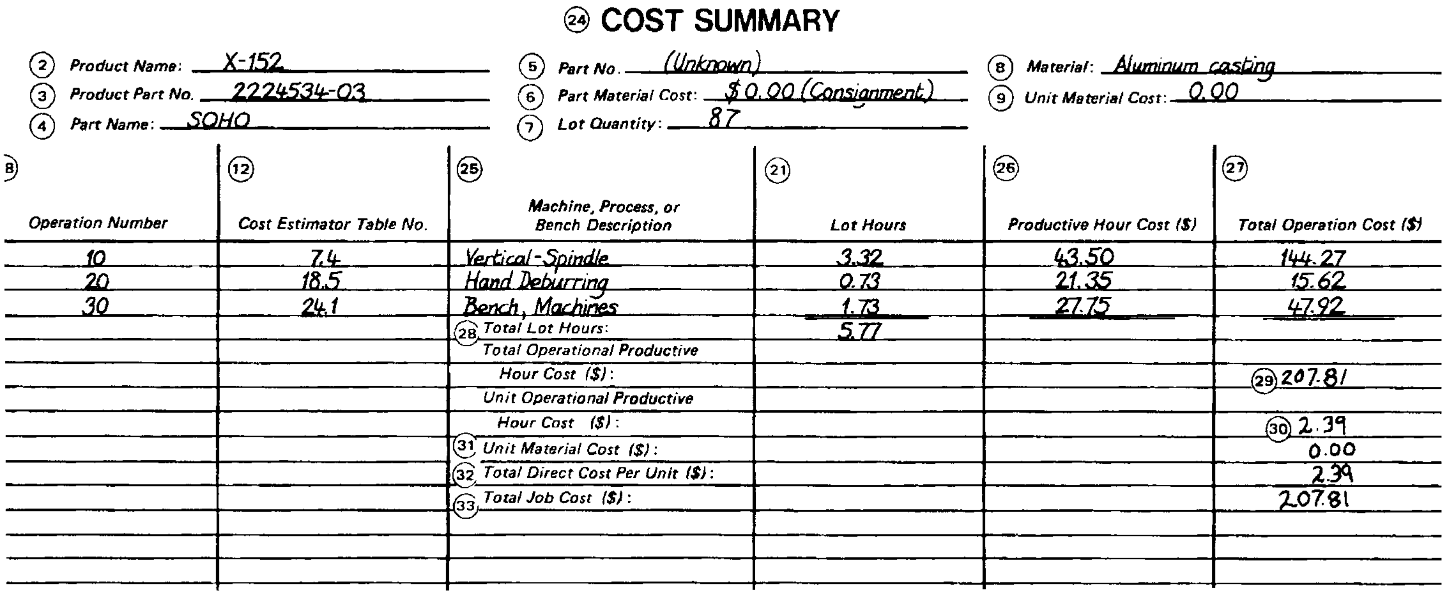
Productive hour cost (PHC) is entered as balloon (26). These company values are the cost for the labor and the machine. Overhead is included for this case. These company values are calculated by accounting.

The lot hours are multiplied by the PHC and given the total operational cost shown in column 27. For example, 3.32 × 43.50 = $144.27. The PHC includes the cost of overhead, and the method can include absorption or activity base methods. The sum of the operation cost is given by the total operational productive hour cost in column 29. The value of $207.81 when divided by the lot quantity of 87 (7) gives the unit operational productive hour cost of $2.39. In this case, this value is for labor and the machine process cost. Because the material is a consignment between the buyer and the manufacturer, no cost is assessed for unit material cost identified by column 31. If a unit cost exists, it is entered here. The sum of the material and the unit operational productive hour cost gives the total direct cost per unit (32). This value is multiplied by the lot quantity and the total job cost is entered in column 33.

This cost summary is used to provide information to the bill-of-material cost summary, which is the means of collecting all costs to obtain the full cost. Except in the case of a single part, the bill of materials is a vital and important document. For those manufacturers who produce only a single part, the cost summary is adequate since it provides the total job cost.

BILL-OF-MATERIAL EXPLOSION FOR PRODUCT ESTIMATES

The estimating of labor and material cost and its extension by overhead calculations will lead to the quantity known as *full cost.* This in turn will be increased for profit to give price. Before that routine is executed, it is necessary to find the total bill-of-material cost for several or many parts, subassemblies, and major assemblies. The bill-of-material explosion is unnecessary if the manufacturer sells only single-item parts, as the cost estimate serves as the principal summary document for price setting. But in the case of several or many parts and assemblies, it is necessary to organize the cost estimates effectively. A bill of material handles a scheme of this organization.



㉔ COST SUMMARY

② Product Name: X-152
③ Product Part No. 2224534-03
④ Part Name: SOHO

⑤ Part No. (Unknown)
⑥ Part Material Cost: $0.00 (Consignment)
⑦ Lot Quantity: 87

⑧ Material: Aluminum casting
⑨ Unit Material Cost: 0.00

8) Operation Number	⑫ Cost Estimator Table No.	㉕ Machine, Process, or Bench Description	㉑ Lot Hours	㉖ Productive Hour Cost ($)	㉗ Total Operation Cost ($)
10	7.4	Vertical-Spindle	3.32	43.50	144.27
20	18.5	Hand Deburring	0.73	21.35	15.62
30	24.1	Bench, Machines	1.73	27.75	47.92
		㉘ Total Lot Hours:	5.77		
		Total Operational Productive Hour Cost ($):			㉙ 207.81
		Unit Operational Productive Hour Cost ($):			㉚ 2.39
		㉛ Unit Material Cost ($):			0.00
		㉜ Total Direct Cost Per Unit ($):			2.39
		㉝ Total Job Cost ($):			207.81

FIGURE 3.4.4 Example of product cost summary.

COMPUTERS AND ESTIMATING

Very few cost estimates are done without the aid of a computer. At the very least, a microprocessor is used for word processing, spreadsheet calculations, database queries, and small, engineer-developed programs. At the other end of the spectrum, companies have developed their own in-house estimating software systems. Some companies with cost estimating expertise have developed commercial cost estimating packages for organizations wishing to use turnkey-type estimating packages.

Computer estimates are very consistent and therefore more accurate. Estimates can be adjusted higher or lower, as needed, or observed from previous cost estimates.

More detail can be incorporated into an estimate because of computers—details that might be tedious and time-consuming if done longhand can be done quickly and accurately on a computer. Work standard data and machining data can be accessed and inserted into an estimate easily. Also, the level of detail relating to risk can easily be determined with the aid of a computer.

Cost estimating software can provide refinements that would not be possible for an engineer to handle. For example, tool types, tool materials, and material conditions can easily and quickly be factored into cost, thus making the estimate more accurate and reliable.

CONCLUSION

Of the many paper or paperless documents a manufacturer will prepare, few are as important as the product estimate. This is the principal figure that the firm will use for pricing. If the cost estimate is such that a profit will ensue, the enterprise continues developing the product. If the estimate gives an indication that a profit is unfeasible in the competitive market, the firm will cancel product development or return the design to engineering for reconsideration, redesign, value engineering, or outsourcing. This chapter has considered the techniques for bringing small pieces of information from data warehouses for the manufacturer to cultivate. This preparation of the cost estimates answers the question, "What will this product do?"

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BIOGRAPHIES

William A. Miller, Ph.D., P.E., is Professor of Industrial Engineering at the University of South Florida, Tampa, Florida. He has extensive experience in manufacturing and over 25 years of university teaching experience. He earned his Ph.D. in Industrial Engineering at Clemson University. Miller is an active member of the Institute of Industrial Engineers (IIE) and the Society of Manufacturing Engineers (SME). He currently is a member of the NCEES, where he is one of the developers of the industrial engineering portion of the P.E. exam. He does active research in automated fixturing systems and control systems for flexible manufacturing systems.

Phillip F. Ostwald is Emeritus Professor of Mechanical and Industrial Engineering, University of Colorado, in the Department of Mechanical Engineering. He has received the Phil E. Carroll Award and the Wellington Award from the Institute of Industrial Engineers.

CHAPTER 3.5

LIFE CYCLE COST ANALYSIS

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Acquiring technical systems and products often involves an extensive and complicated interaction between the customer and its contractor. The common efforts determine whether the system or end product is going to fulfill the customer's needs in functional terms, at a reasonable total cost over the life of the system or product. One acquisition technique, which has received growing attention in recent years, has been termed *life cycle cost* (LCC) or cost of ownership. Different aspects of LCC methodology applied in acquisition of technical systems and products process will be discussed in this chapter.

LIFE CYCLE COST—WHY AND HOW

Technical acquisition refers to the process of acquiring a complete technical system or equipment (the product), comprising the development, building, testing, and setting into operation of this system together with the creation of a suitable organization for equipment operation and support.

Technical acquisition often involves a complicated interaction between the customer and its contractor. The common efforts of these two parties determine whether the end product is going to fulfill the needs of the customer *at the lowest possible total cost during the life span of the product.*

The acquisition techniques adopted will—generally speaking—guide the contractor toward the customer objectives, and will have a critical impact on the end product solution in technical, functional, and financial terms. One acquisition technique, *life cycle cost* (LLC), or *cost of ownership,* is now receiving considerable attention.

LCC—What Does It Mean?

Life cycle cost is commonly understood to be the customer's (buyer's or user's) total cost plus other expenses incurred during the lifetime of the product. Therefore, LCC includes the acquisition cost as well as all future costs for operation and support of the product until it is finally discarded.

LCC means that

- *Prior* to the decision on the acquisition of a product and the source selection, the customer wants to know the total cost of ownership: "To which future costs do I commit myself by choosing this product today?"
- *After* the decision on the acquisition of a product and the source selection, the customer wants to be able to monitor and control the evolution of ownership costs: "How can I ensure that a concept of the product keeps the ownership costs within budget?"

To maintain control of the cost of ownership, the contractor must carry out appropriate activities regarding ownership throughout the entire acquisition process.

Reasons for Taking LCC into Account

By tradition the acquisition effort has highlighted the technical performance, the price, and the delivery schedule of the product. These explicit priorities of the customer are well recognized by the contractor and the result is an unbalanced requirement specification, as illustrated in Fig. 3.5.1.

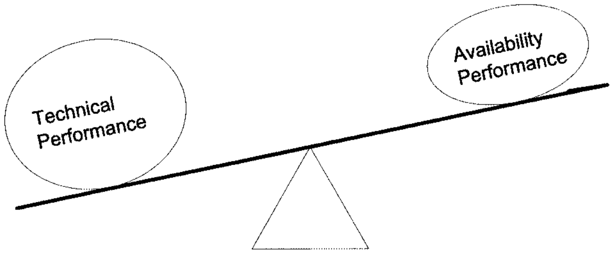

FIGURE 3.5.1 Unbalanced requirements specification.

The incentive for the contractor to put higher value on product reliability and maintainability can be derived only from the customer. In this area LCC has proven itself to be a successful tool. LCC is closely related to the product's reliability, since it is the lack of good availability performance indicators that costs money during the operations and support phase. This is illustrated in Fig. 3.5.2, which shows how the reliability aspect is becoming a greater concern in product design due to the financial incentive to provide enhanced availability performance and reduced maintenance costs. (There is considerable risk if the teeterboard tips too much toward LCC. A balanced situation offers the best total solution.)

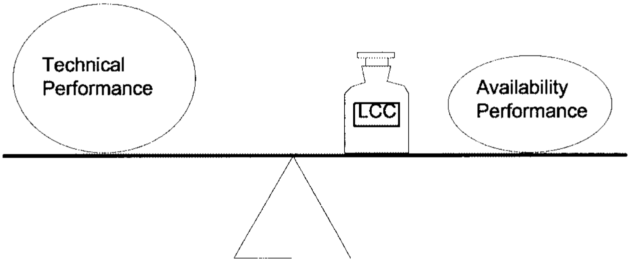

FIGURE 3.5.2 Balanced requirements specification.

A summary of the reasons for implementing LCC states:

> The customer desires satisfaction of a given need for a specific functional performance at the lowest possible total cost taking into account the total operational lifetime of the product.

With this in mind we should identify LCC from the very start as an important factor in our decision process, together with other factors such as technical performance and availability performance.

Calculation of LCC

LCC should become a tool for product selection as well as for guidance of the product design to accomplish the desired operational performance at the lowest total cost. If LCC also is to become the control tool the customer needs for the acquisition process, the LCC effort must be planned to provide the following:

- Development of alternative product/maintenance solutions to reduce LCC
- Calculation of LCC for each alternative
- Means for compliance assessment
- Calculation of resources required, such as increased acquisition cost

From these requirements we can extract four separate areas of the acquisition process where LCC is useful:

1. For study and investigation purposes, in feasibility analysis, and for development of performance/cost relationships and system concepts
2. As an assessment tool during the product development phase, with the purpose *to aid the user* in determining if an alternative design solution is superior to the previously presented basic solution
3. As a source selection tool in the acquisition process
4. As a contracting tool to ensure that the aspects of availability performance and maintenance support are considered in the contract

Description of LCC Cost Elements

The primary cost elements in the LCC calculation model are the following:

$$\text{LCC} = \text{LCA} + \text{LSC}$$

where LCC = life cycle cost
LCA = acquisition cost (product price)
LSC = life support cost (user cost)

The costs, so-called relevant costs, that should be included in a calculation of LCC cannot be stated in general, since they are dependent on the actual application. Therefore, the calculation of LCC must be adjusted to the actual decision case. The selection of relevant cost elements has to be guided by the expected significance due to tenderers (of a contract proposal), designs, or maintenance solutions.

In a normal case the following cost elements will be included in LSC:

- Cost for corrective maintenance, on-site as well as workshop maintenance
- Cost for preventive maintenance

- Cost for spares, initial investment, and substitutes for future consumption (both reparable and discardable line replaceable units [LRUs])
- Cost for maintenance tools and equipment
- Cost for documentation
- Cost for training
- Cost for operation
- Cost for lost production due to product downtime (unavailability time)
- Cost for those remaining items that are deemed significant

These cost elements are derived from relationships between each cost element and the project properties. The equations used for LCC calculations will convert project properties into costs. Note that the equations will only approximate and do not express actual costs. An approximation of reality always portrays a simplified image and can never completely cover all aspects of the real situation. In spite of this, the equations' usefulness in the project process is good, because the calculation of LSC is not an objective in itself, but a *means* to control the real LSC result.

LCC Acquisition Strategy

In the initial phase of the acquisition, it is of fundamental importance to make the prevailing criteria quite clear—to oneself and to potential contractors:

- Technical performance requirements shall be fulfilled.
- Availability performance requirements shall be fulfilled.
- Deviation from the technical as well as from the availability performance requirements may be accepted at the customer's discretion, provided that substantial savings are accomplished. The decision will be based on a cost/requirement trade-off analysis.
- Source selection is based on the calculated LCC being the total weighted cost for
  - Acquisition of the product including the maintenance resources.
  - Estimated cost for x number of years of operation and support.

LCC Request For Proposal

To achieve full LCC benefits in a product development contract, it is important to achieve an active tenderer/contractor contribution to the LCC analysis effort. The request for proposal (RFP) should include the following:

- The customer's approach to the acquisition process.
- The allocation of commitments that apply during different phases (in tenders as well as in contracts).
- A preliminary description of the tender evaluation model. In this regard the customer should
  - Specify the required data.
  - State that the result of the customer's calculations will be fed back to the respective tenderer.
  - Give notice of the customer's intention to discuss model improvements, if any, with the tenderers.
  - Declare the customer's intention to support the tenderer with a reasonable amount of computer processing, in case the model will require special aids like computer programs.

The following outline lists typical headings for a chapter on availability performance and LCC in an RFP.

PRODUCT X
Availability Performance and Life Cycle Cost

1. INTRODUCTION
2. PRINCIPLES FOR THE EVALUATION OF PROPOSALS
  2.1. General Conditions
  2.2. Evaluation Criteria
3. DEFINITIONS
  3.1. Availability Performance
  3.2. Reliability Performance
  3.3. Maintainability Performance
  3.4. Supportability Performance
  3.5. Equipment Structure
  3.6. Maintenance Equipment
  3.7. Lifetime
  3.8. Life Cycle Cost (LCC)
4. COMMITMENT AND VERIFICATION
  4.1. Commitment of Life Cycle Cost
  4.2. Verification of Life Cycle Cost
5. CONDITIONS FOR OPERATION AND MAINTENANCE
  5.1. Scope
  5.2. Operational Profile
  5.3. Environmental Conditions
  5.4. Maintenance and Support Organization
6. AVAILABILITY REQUIREMENTS
  6.1. Reliability Requirements
  6.2. Maintainability Requirements
  6.3. Supportability Requirements
7. OPERATIONAL AND AVAILABILITY DATA TO BE INCLUDED IN THE PROPOSAL
  7.1. Purpose
  7.2. Prerequisites
  7.3. Reliability Data
  7.4. Maintainability Data
  7.5. Supportability Data
  7.6. Operational Data

Functional Requirements Related to LCC

The ability of the product to provide the specified functional performance when failures, disturbances, and limited maintenance resources affect the product is related to the requirements of availability performance and LCC. The following functional requirements are commonly used to evaluate availability performance:

- Requirement on reliability, which can be measured in failure rate or MTTF (mean time to failures)
- Requirement on maintainability, which can be measured in MTTR (mean time to repair)
- Requirement on supportability, which can be measured in MTW (mean time waiting), MLDT (mean logistics downtime), and others

- Requirement on availability, which is the cumulative effect of these product properties and can be measured in availability or downtime
- Requirement on LCC or LSC

Which requirement or combination of requirements should be used in a specific case depends on the priorities of the user that relate to the operation of the product. Also, the user's costs for unavailability and maintenance of the product are important factors that will affect the combination of requirements used. The matrix in Fig. 3.5.3 shows some of the theoretical combinations of requirements.

	Availability	Maintenance Cost	Reliability	Maintainability	Lifetime
Downtime causes huge costs	X			X	
Operation is a must, e.g., a safety device			X		
Failures cause or may cause serious consequences			X		
Large purchase price and long technical lifetime	X				X
Maintenance cost is an essential part of life cycle cost		X			
Maintenance times cause an essential part of life cycle cost		X		X	

FIGURE 3.5.3 Combinations of requirements.

LCC Evaluation Techniques

The objective of the customer's quantitative evaluation of reliability and maintainability characteristics is to provide answers to the following three questions:

1. Is every availability performance requirement in the RFP fulfilled by each tenderer?
2. Which tenderer has a product offering the best functional availability characteristics under the specified operational conditions?
3. Which tenderer has a product offering the lowest expected cost for acquisition, operation, and support during the lifetime of the product under the specified operational conditions?

Parallel to this quantitative evaluation, there is a qualitative evaluation intended to assess those product characteristics that do not lend themselves to numerical representation, such as ergonomics.

The work procedure of the LSC evaluation is summarized here:

- Calculate failure rates (failure flows), repair times, and costs for consumption of spare material.
- Calculate several key figures expressing product availability performance characteristics.
- Calculate the investment cost of spares (line replaceable units). The calculation is related to the required availability of the product and to the user's maintenance organization.
- Calculate the accumulated LSC according to the specific project model (equation). This result is then added to the acquisition cost to achieve the total LCC.
- Review the calculated results through a sensitivity analysis; check and revise all input data.
- Present the compiled results to each tenderer (of course, its own result only). With guidance by this report, each tenderer may be given the opportunity to adjust its tender within a given time frame, after which the same sequence is repeated.

Note that the information and intermediate results are continuously checked for relevancy during all phases of the quantitative evaluation. Computer software capable of performing these work procedure calculations is available in the commercial market.

The LCC Contract and LCC Verification

The contract contains *the contractor's guarantee that the accumulated product* (*system*) *LCC,* calculated and verified according to the specified model, *will not exceed the contracted limit.*

The contractor is *not* held responsible for any actual outcome of the future operation and support costs, which is entirely consistent with the discussion regarding the scope of LCC calculations.

As a complement to the LCC commitment, the contractor is sometimes *also* required to guarantee *isolated* availability performance characteristics, for example, minimum acceptable mean time to failures or maximum acceptable time to repair. This might be relevant if any such characteristic is expected to dominate the customer options regarding the use or maintenance of the product.

Attached to the commitment (guarantee) is a remedy for noncompliance. The principle requires the contractor to compensate the customer for the difference between the verified LCC outcome and the guaranteed LCC value. The compensation may take the form of delivery of free spares and/or some other monetary form. Modification of the product—at no cost to the customer—to render it LCC compliant in the future is usually included in the compensation. The composition and magnitude of the compensation from the contractor to the customer should be *realistic* and *reasonable* with regard to the agreement in its entirety between the parties.

The structure and the drafting of an LCC contract varies from case to case according to the actual acquisition situation.

To verify LCC means to test and confirm that LCC according to the specified calculation model does not exceed the contracted limit value. The LCC is no different from any other contract requirement; it must be subject to verification using the agreed-to model, unless it is obvious to the customer that the requirement is met. This is why the customer should reserve the option of acceptance without verification.

The contract clauses on verification should include the following:

- The verification procedure
- When and what objects will be subject to verification
- Acceptance or rejection criteria to be applied to the verification results
- Other rules for verification conduct

The verification of LCC means that the various cost elements that together equal the total LCC value must be verified. Certain cost elements, such as training and documentation costs, are easily verified—as priced by the contractor. Other cost elements are verified by verification of the product characteristics determining the actual cost element by an equation in the model (using actual occurred failures and times to repair).

The contractor normally is committed to only *the total weighted result* from all the separate model factors that determine if the LCC requirement is met or not; there is no guarantee of separate reliability or maintainability characteristics, such as failure rate, even if such specific factors are subject to verification. In this way the contractor has the opportunity to improve on its situation by changing one of the model factors under its control: for example, by adjusting the pricing of spares.

Reminder for the LCC Acquisition

Experience from previous acquisition projects indicates that certain conditions and work elements specifically influence the possibility of performing a successful LCC acquisition and achieving good results:

- Resources
- Preparations
- Data collection
- Contractor negotiations

For a medium-size acquisition project the following staff configuration may be appropriate:

- One manager/coordinator
- One specialist in LCC techniques
- One product specialist

An important factor in achieving good work efficiency is the support of a powerful and readily available computer system including all the programs required for the evaluation effort.

The need for evaluation resources depends on several factors: number of tenderers, tender quality with respect to completeness and disposition, calendar time available, and ambition level of the evaluation considering project size, know-how, and acquired experience within the customer staff.

The evaluation effort can be reduced by developing schedules, resource allocations, tasks and responsibilities, and so on in an *early* stage of the project. A test evaluation should be performed with simulated input data, sometimes known as a *dry run,* prior to the start of the actual evaluation. The purpose of this dry run is to determine the proper work procedures, make the final computer program check, find appropriate means for communication and reporting, and otherwise identify improvements that simplify the processing of the tenders.

A thorough specification of the reliability and maintainability data required for tender evaluation is a must in the request for proposal. Nevertheless, tenders will show various degrees of incompleteness. One task in the primary tender review must be to identify shortcomings. An alternative is to insert the customer's own guesstimates in place of the missing data items. A better way may be to inform the tenderer—*immediately* following the completion of the primary review—of the insufficient parts of its tender and to allow the tenderer a short but reasonable time to provide supplementary data.

When the LCC calculation result is available, it is customary to notify each tenderer about its performance (provide feedback). Usually the tenderer's response is to request permission to introduce some changes to the original data set. Not counting the initial supplements mentioned in the previous paragraph, one or two rounds of adjustments are normal.

When *direct negotiations* are in progress, it is extremely important that the customer keep its freedom of action, which of course, is true in most negotiation situations. One way to achieve this is to perform simultaneous negotiations with two or three of the most appealing tenderers. Because of the often limited resources, it is advisable to carry out the negotiations during short concentrated meetings at scheduled intervals. If desirable, these negotiations may be continued with perhaps two tenderers—up to the point when the customer is ready to sign one of two complete contracts.

Addressing availability performance and LCC issues early in the initial negotiation stage is important to facilitate parallel discussions and to allow for desirable reciprocal trade-offs.

LCC ACQUISITION OF TRACK MAINTENANCE MACHINES—A CASE STUDY

Acquisition Characteristics

Railway track maintenance is performed using various types of machinery. This case study addresses a LCC acquisition program of tamping machines for use by the Swedish State Railways (SJ).

The availability performance of a machine has a crucial impact on what the machine can produce in real-life. Design principles, selection of components, and maintenance organization have an impact on both availability performance and LCC. Specified true functional performance to lowest LCC has been used as the criterion for the source selection decision.

The acquisition in this case study was accomplished in two phases:

Phase 1. Conducted an availability performance and maintenance cost study of existing tamping machines within SJ. The purpose was to be able to establish requirements for the new machines as a baseline for the LCC evaluation.

Phase 2. Monitoring of the preparation of the RFP, calculation and analysis of availability performance and LCC for tenders, discussions with tenderers about potential improvements, negotiations with tenderers, definition of the LSC contract, and related verification procedures.

Request for Proposal

The major sections of the RFP included

- Principles and considerations for the evaluation of tenders.
- Calculation of LCC.
- Contractor undertakings and verification of LCC.
- Conditions and constraints for operation and maintenance.
- Availability performance and cost data, which were required for the tender. Examples of such data include failure rates and repair times for line replaceable units (spares), the need for preventive maintenance, maintenance aids, documentation, and training costs.

LCC Model

Calculation of LCC was limited to include the following cost elements:

$$\mathrm{LCC} = \mathrm{LCA} + \mathrm{LSC}$$

$$\mathrm{LSC} = \mathrm{CIR} + \mathrm{APD} \times (\mathrm{CYA} + \mathrm{CYE} + \mathrm{CYC} + \mathrm{CYR} + \mathrm{CYO})$$

where LCA = acquisition price
LSC = life support cost
CIR = investment in spares
APD = discounting factor
CYA = annual cost for corrective maintenance
CYE = annual cost for preventive maintenance
CYC = annual cost for repair of repairable spares at central workshop
CYR = annual cost for consumption of nonrepairable spares
CYO = annual cost for operation

Analysis Results

The cost distribution of LSC cost elements for one type of tamping machines can be seen in Fig. 3.5.4. The annual cost for corrective maintenance, CYA, could be influenced by changes in the design of the machine, which would lead to lower failure rate and improved maintenance. Additionally, such changes would have a positive impact on the cost elements CYC, CYR, and CIR. The conclusion was that improvements in reliability performance and maintainability could have a substantial impact on the LSC for the machine. An analysis of the components in the machine would reveal what the major cost generating items are and give guidance for potential improvements.

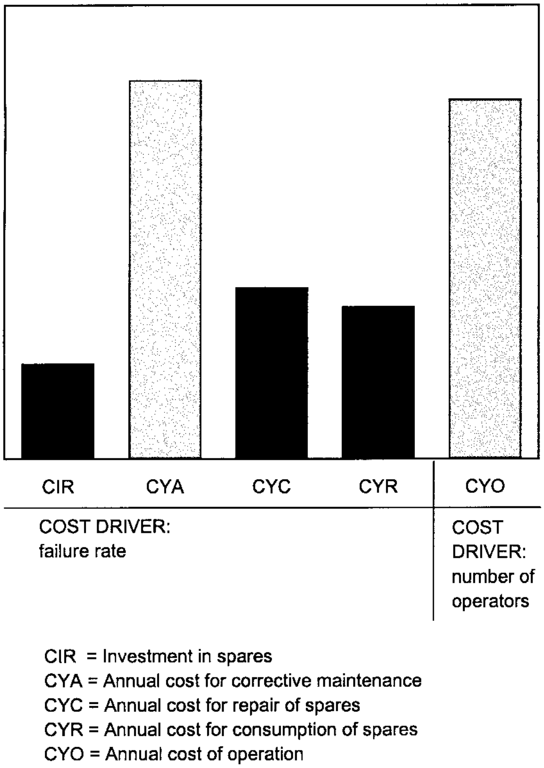

FIGURE 3.5.4 Distribution of LSC cost elements.

The result of such an analysis performed by using a computerized calculation procedure is shown in Fig. 3.5.5. The figure shows the order of precedency for some types of components with regard to their contribution to certain reliability and cost characteristics. Only the 6 worst types in each group out of the examined 160 items are displayed. Figure 3.5.5 depicts the following results:

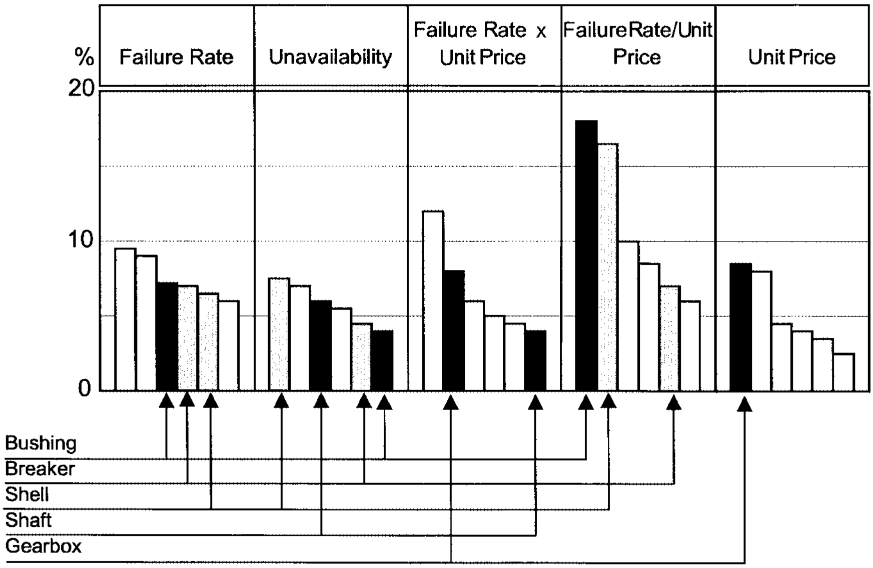

FIGURE 3.5.5 Component analysis.

- Six types contribute to 40 percent of the total failure rate
- One type has 10 percent of the maintenance cost (component failure rate multiplied by component price)
- Two types dominate in the category of probable bad quality (component failure rate divided by component price)
- Some types of components (such as bushings, breakers, and shells) are found in several groups. These types of components are of special interest in finding candidates for LSC improvements.

The results were presented to the respective tenderers with a request for a review and comments. Each tenderer was encouraged to make adjustments to the tender within two weeks, after which a second LCC calculation followed. The corresponding result, status 1 in Fig. 3.5.6, became subject to the previously described procedure. As a result of this second review, some minor adjustments in input data were made and a final LCC was calculated: status 3 in Fig. 3.5.6. The result was used in the source selection decision process.

Figure 3.5.6 shows gradual improvements in LCC. Some major factors causing these improvements were

- More cost-effective adaptation of preventive maintenance leading to decreasing cost for corrective maintenance
- Adaptation of spares policy and allocation considering failure influence on machine availability

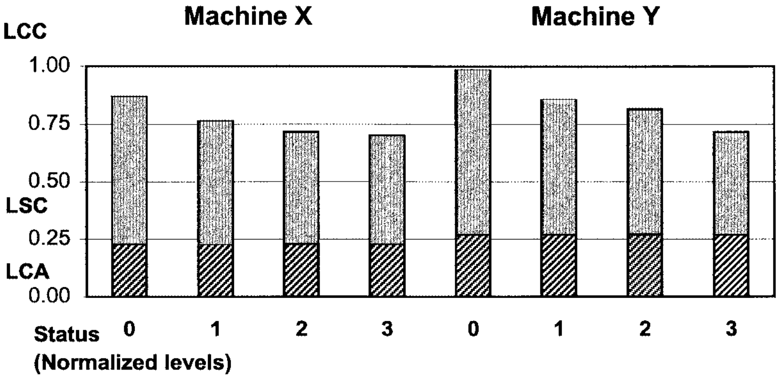

FIGURE 3.5.6 Result of LCC calculations, status 0,1,2, and 3 for the two most interesting tenders.

The LSC Contract

Contract negotiations were initiated with the two most interesting tenderers. An agreement was reached between SJ and the contractor, which included an LSC undertaking, meaning that the contractor warrants that the LSC for the delivery will not exceed a specified limit—contractual LSC—extracted and defined from the LCC status 3 result.

Condensed directions and guidelines for verification of LSC and reliability performance are included in the contract. The remedy in case of an exceeded LSC is also stated. If the verified LSC exceeds the contractual LSC, the contractor should redesign, modify, or exercise any other action to bring the LSC back to the contractual limit. All activities will be without any additional cost to SJ, providing that SJ's time schedule for the use of the machines permits: If this is not the case the contractor should financially indemnify SJ by supplying more spares free of charge, reducing contract price, or paying a penalty. The actual compensation should be negotiated based on the difference between the values of verified LSC and contractual LSC.

The calculation of contractual LSC and verified LSC performed according to a slightly modified LSC model. This model covers only cost elements, which are influenced by failure flows.

The verification of LSC was performed by a demonstration on machines in actual operation. The machines were followed during a specified period of time (typically six months up to one year) during which malfunctions and their causes were verified and ascertained. A standard statistical verification procedure was used.

The results fulfilled the contractual commitments and the original objective of this LCC acquisition was well met.

LESSONS LEARNED FROM LCC ACQUISITIONS

The experience can be summarized by the following remarks:

- Make clear why LCC techniques should be applied
- Aim at specifying functional performance to avoid technical constraints
- Clearly state in the RFP the principles for tender evaluation and data requirements
- Specify at an early stage provisions for verification of contractual commitments

- Prepare for tender evaluation by using fictitious data in a preliminary analysis and LCC calculation
- Expedite a request for any missing data immediately on receipt of tender
- Inform each tenderer about its own LCC result
- Make sure that the time schedule allows for potential LCC improvements and provide a reasonable time for the tenderer/contractor to complete changes

Heeding these lessons will facilitate the LCC acquisition process and benefit the parties involved.

FURTHER READING

Borghagen L., and L. Pålsson, "Evaluation and Improvements of Life Cycle Cost—Rapid Trains, Train Communication Systems and Other Cases, *Rail International* no. 2/1985. (journal)

International Standard IEC 300-3-3, Dependability Management, Application Guide: Life-Cycle Costing, International Electrotechnical Commission, Geneva, Switzerland, 1996.

International Standard IEC 300-3-4, Dependability Management, Application Guide: Guide to the Specification of Dependability Requirements, International Electrotechnical Commission, Geneva, Switzerland, 1996.

BIOGRAPHY

Lennart B. Borghagen holds an M.Sc. in electrical engineering from Chalmers University of Technology in Gothenburg, Sweden. He is employed by the Swedish Defence Material Administration (FMV) in Stockholm, as director of procurement. Prior to his present employment, Mr. Borghagen was with the Swedish State Railways (SJ) as senior manager for the Life-Cycle Cost Applications Group within SJ's Fixed Installations Department. He is currently a member of the board of directors of the Swedish Association of Public Purchasers, and has authored a number of technical papers and reports in the fields of reliability, life cycle costing, and procurement methodology.

Source: MAYNARD'S INDUSTRIAL ENGINEERING HANDBOOK

CHAPTER 3.6

CASE STUDY: IMPLEMENTING AN ACTIVITY-BASED COSTING PROGRAM AT AUTO PARTS INTERNATIONAL

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Activity-based costing (ABC) became popular in the late 1980s as companies realized that traditional cost accounting systems were inadequate. Traditional systems were designed for financial reporting and tax purposes rather than management decision making and control. These systems are typically high level summaries based on simplistic product costing methods. Operating managers need information that is up-to-the-minute, detailed, and highly accurate to perform their jobs efficiently and effectively.

This case study illustrates how the management of a typical manufacturing company recognized the need for better cost information and the process they followed as they designed and implemented their ABC system. It describes how the members of the ABC implementation team, including the industrial engineer, performed their assigned tasks and interacted throughout the entire process. The case, although fictitious, is based on actual client situations. It will therefore provide the industrial engineer with a realistic example of what is required to implement a successful ABC program. For a description of an ABC system see Chap. 3.3.

ABC BASICS

In manufacturing environments, accountants have traditionally allocated the overhead costs—such as supervisory, quality assurance, engineering, and other indirect salaries; depreciation; supplies; and maintenance labor and supplies—to the firm's products, using a single arbitrary allocation basis such as direct labor hours. Fifty years ago, when direct labor costs comprised the majority of expenditures and indirect costs were a minor expense, this treatment may have been adequate. Today, the situation is reversed: Indirect or overhead costs make up the bulk of costs, so more care should be taken when they are attributed if products are to be accurately costed. Rather than the traditional one-stage allocation on a single basis, ABC uses a two-step process, as shown in Fig. 3.6.1. ABC models the consumption of costs from resources through activities to products or other cost objects, such as customers or channels of distribution.

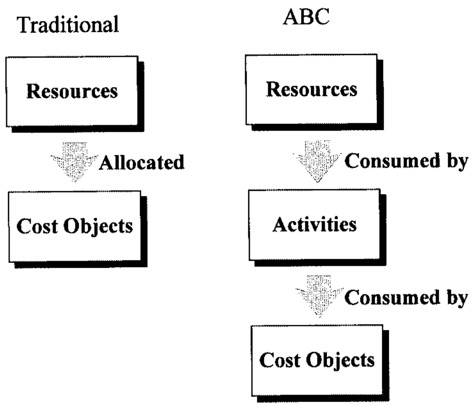

FIGURE 3.6.1 Traditional costing versus ABC.

Let's say, for example, an accountant determines that overhead expense is expected to be three times the direct labor expense for the coming year. Using the traditional accounting method, the accountant would then, over the course of the year, allocate $3 of overhead to a product for $1 of direct labor spent on that product. The shortcoming of this method becomes apparent if the organization produces more than one product, because the true patterns of overhead expense consumption will likely differ for each. Rather than allocating the whole pool of resource costs on one basis, the ABC method traces how the various parts of the resource pool are consumed by the products. Because of the additional step (allocating to activities) and the use of multiple allocation bases (cost drivers) an example becomes quite complex. The following fictional case study on Auto Parts International will illustrate the ABC method.

BACKGROUND—AUTO PARTS INTERNATIONAL

Auto Parts International is a Canadian company with eight plants operating in southwestern Ontario, Canada. Its head office is in Cambridge, Ontario. Each plant produces parts such as mufflers, brake rotors, and gaskets, primarily for original equipment manufacturers (OEMs) in the automotive industry.

Jeremiah Kingston, the president, heard about ABC from his vice president of finance, Ted Jones, and thought it would benefit his firm. While Auto Parts International was realizing a profit, neither Jeremiah nor Ted had a good understanding of which products, or customers, were profitable or why. Jeremiah believed that such information would help him manage the firm to higher levels of profitability.

The Brake Rotor Division, located in Brantford, Ontario, was chosen for a pilot study, and consultants from KPMG Consulting were brought in to work with the division's staff to develop an ABC system. This division was chosen because it was fairly small, manufacturing only a few products; further, it was only marginally profitable. Jeremiah and Ted felt that this project was small enough to quickly test how ABC would work, before they committed to a companywide implementation. It was also an opportunity to address the division's marginal profitability. Table 3.6.1 shows the division's latest income statement. (All financial data is based on 1996 figures.)

TABLE 3.6.1 Income Statement

Revenue		$8,793,678
Direct Labor	1,638,000	
Raw Material	3,073,139	
Packaging	89,577	
Cost of Goods		4,800,717
Gross Margin		$3,992,961
Departmental Expenses		
Production	256,250	
Quality Assurance	221,200	
Engineering	224,500	
Maintenance	334,400	
Shipping/Receiving	362,800	
Customer Service	146,600	
Sales	530,200	
Finance	332,500	
Executive	189,200	
IT	294,700	
Human Resources	109,500	
Plant Management	953,900	
		3,955,750
Gross Profit		$37,211

The Brake Rotor Division produces four different brake rotors, which are sold to three automotive OEMs and to a number of distributors for the service market. Figure 3.6.2 illustrates how the Brake Rotor Division's staff is organized.

An ABC model was created to break down the income statement accounts and provide information about product and customer profitability.

MODEL DEVELOPMENT

Project Organization and Information Gathering

When Jeremiah and Ted decided to proceed with this project, they both agreed that it was very important that this not be just another accounting exercise. Accounting would participate, but Jeremiah and Ted wanted to make sure the model reflected the operational realities of the plant. Accordingly, they decided that the project should be headed by an

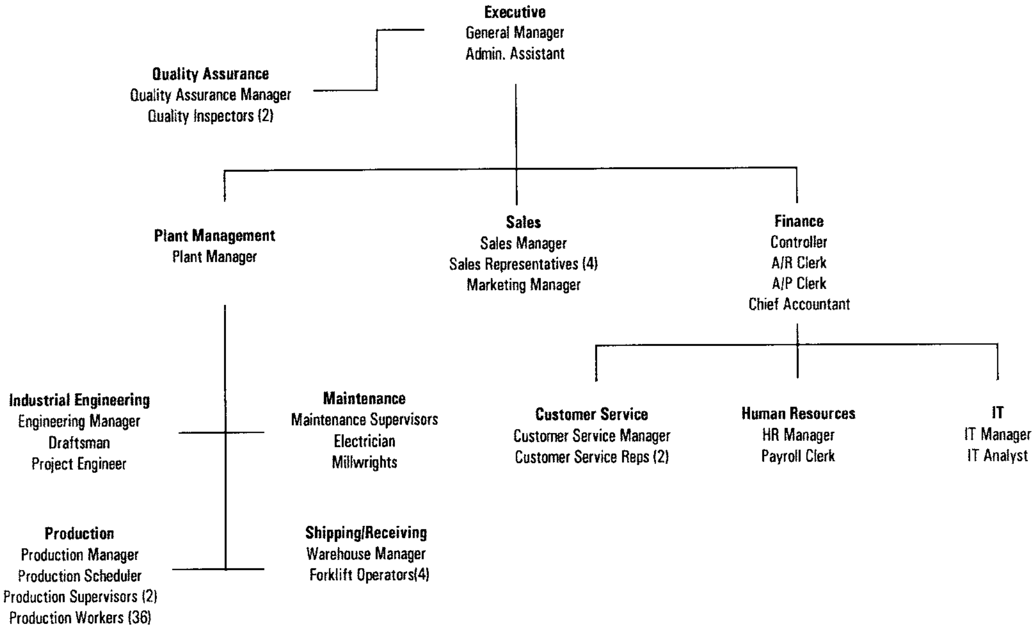
Executive
General Manager
Admin. Assistant
Quality Assurance
Quality Assurance Manager
Quality Inspectors (2)
Plant Management
Plant Manager
Sales
Sales Manager
Sales Representatives (4)
Marketing Manager
Finance
Controller
A/R Clerk
A/P Clerk
Chief Accountant
Industrial Engineering
Engineering Manager
Draftsman
Project Engineer
Maintenance
Maintenance Supervisors
Electrician
Millwrights
Customer Service
Customer Service Manager
Customer Service Reps (2)
Human Resources
HR Manager
Payroll Clerk
IT
IT Manager
IT Analyst
Production
Production Manager
Production Scheduler
Production Supervisors (2)
Production Workers (36)
Shipping/Receiving
Warehouse Manager
Forklift Operators(4)

FIGURE 3.6.2 Auto Parts International—Brake Rotor Division organization chart.

industrial engineer—that is, someone with considerable skills in analyzing integrated systems of people, material, information, equipment, and energy. Furthermore, someone with an industrial engineering background will possess knowledge and skills in the mathematical, physical, and social sciences, which are needed to effectively lead an ABC project. Bill Burley, the plant industrial engineer, was therefore asked to head the project. Bill formed a team that included a KPMG consultant, Frank Smith; the controller, Jane French; and the IT analyst, Tom Douley, and began the project by interviewing the other employees. Through the interviews, they determined what activities these employees performed and the amount of time spent on each, the purpose of the activity, and the cost driver (what caused the activity to occur). While some employees were initially concerned when the interviewers asked questions about their jobs, most relaxed and found the sessions informative.

After completing the interviews, Jane, the controller, began using the information to break down the general ledger costs into activity costs. Table 3.6.2 shows the annual expense report for the finance department with a resource driver assigned to each account.

Using Resource Drivers

The resource driver is the allocation method for breaking down the general ledger accounts (resources) to activities. Two of the methods—Time Spent, and Headcount were developed from the interview results (see Table 3.6.3). Bad Debts directs the cost of bad debts to Collect Receivables, Audit Fees assigns the cost of the external accountants to the activity, Prepare Financial Statements, and Travel allocates the cost of travel to the appropriate activities. Table 3.6.3 shows the interview results, and the salary, wage, and benefit information from the pay-

TABLE 3.6.2 Finance Department General Ledger Accounts

Accounts	Resource Driver	Balance
1 Salaries and Wages	Time Spent	$170,000
2 Benefits	Time Spent	34,000
3 Occupancy Charge	Headcount	24,800
4 Miscellaneous	Headcount	2,300
5 Bad Debt Expense	Bad Debts	65,000
6 Audit Fees	Audit Fees	30,000
7 Travel	Travel	6,400
Total		$332,500

roll system for the finance department's employees. Table 3.6.4 shows the results of the activity cost calculations.

Time Spent Resource Driver. The Time Spent resource driver column in Table 3.6.4 shows the amount of personnel costs: salary, wage, and benefits dollars that were consumed by the different activities. This data was derived from the information in Table 3.6.3. For example, the Time Spent amount for Prepare Financial Statements was determined as follows:

TABLE 3.6.3 Finance Department Employee Information

Controller		
Salary		$65,000
Benefits		13,000
Total	100%	$78,000
Analyze Sales Trends	10%	7,800
Attend Trade Shows	5%	3,900
Collect Receivables	5%	3,900
Evaluate Capital Expenditures	5%	3,900
File Tax Returns	20%	15,600
Personnel Administration	10%	7,800
Prepare Business Plan	20%	15,600
Prepare Financial Statements	25%	19,500

Accounts Receivable Clerk		
Salary		$30,000
Benefits		6,000
Total	100%	$36,000
Collect Receivables	50%	18,000
Prepare Financial Statements	50%	18,000

Accounts Payable Clerk		
Salary		$30,000
Benefits		6,000
Total	100%	$36,000
Process Payables	100%	36,000

Accountant		
Salary		$45,000
Benefits		9,000
Total	100%	$54,000
Analyze Sales Trends	20%	10,800
Evaluate Capital Expenditures	5%	2,700
File Tax Returns	5%	2,700
Prepare Business Plan	10%	5,400
Prepare Financial Statements	40%	21,600
Process Payables	5%	2,700
Purchase Packaging	6%	3,240
Purchase Raw Material	9%	4,860

TABLE 3.6.4 Finance Department Activity Cost Calculations

		Salaries & Wages	$170,000	Occupancy Change	$24,800							
		Benefits	34,000	Miscellaneous	2,300	Audit Fees	$30,000	Bad Debt Expense	$65,000	Travel	$6,400	Support
Activity	Activity Cost		$204,000	Headcount	$27,100	Audit Fees	$30,000	Bad Debts	$65,000	Travel	$6,400	Reallocation
Analyze Sales Trends	$23,506		$18,000	$0.30	$2,033							$2,873
Attend Trade Shows	11,118		3,900	0.05	339					100%	$6,400	479
Collect Receivables	95,893		21,900	0.55	3,726			100%	$65,000			5,267
Evaluate Cap Exp Requests	8,236		6,600	0.10	678							958
File Tax Returns	22,388		18,300	0.25	1,694							2,394
Personnel Administration	1		7,800	0.10	678							(8,477)
Prepare Business Plan	25,906		21,000	0.30	2,033							2,873
Prepare Financial Statements	107,903		59,100	1.15	7,791	100%	$30,000					11,012
Process Payables	55,869		38,700	1.05	7,114							10,055
Purchase Packaging	4,222		3,240	0.06	407							575
Purchase Raw Material	6,332		4,860	0.09	610							862
	$361,371		$204,000	$4.00	$27,100	100%	$30,000	100%	$65,000	100%	$6,400	$28,871
Less: Support Activities	$28,871											
General Ledger Balance	$332,500											

* See Table 3.6.3 for details on Time Spent.

Controller: 25% of $78,000 ($65,000, salary plus $13,000, benefits)	$19,500
Accounts Receivable Clerk: 50% of $36,000 ($30,000, wages plus $6,000, benefits)	$18,000
Accountant: 40% of $54,000 ($45,000, salary plus $9,000, benefits)	$21,600
Total	$59,100

With the exception of the wages for the operators on the production line, the rest of the employee costs were broken down in a similar manner. The production labor was treated differently since a labor tracking system had been installed by Bill prior to the start of this project. The operators on the production line coded their time to both a short list of activities—Set Up Production, Run Production, Production Downtime, and Package Aftermarket—and the product being run. While the estimates obtained through the interviews were adequate for the first trial of the ABC system, Bill agreed with the team that in the future several other staff members such as the quality inspectors, millwrights, and electricians should be tracked by this system as well.

In the general ledger, Jane accounts for the cost of office supplies, office equipment, and telephone charges centrally, and then assigns these costs to departments on the basis of headcount through the Occupancy Charge account. Space and utilities costs are charged to this account on the basis of square footage occupied.

Headcount Resource Driver. The Headcount resource driver breaks down the cost of the Occupancy Charge to the relevant activity. Since it was believed that employees within each department had relatively equal access to services, the cost was assigned to activities on the basis of departmental headcount. The numbers for the Headcount column in Table 3.6.4 were developed from the interview results in Table 3.6.3. For example, the headcount of 1.15 for Prepare Financial Statements was calculated as follows:

		Headcount
Controller—25% of her time	=	.25
Accounts Receivable Clerk—50% of her time	=	.50
Accountant—60% of his time	=	.40
Total		1.15

The cost associated with the Occupancy Charge adds another $7,791 to the cost of the activity, Prepare Financial Statements. In addition to the compensation and occupancy costs, Prepare Financial Statements requires the help of the external auditors. Adding the audit fees of $30,000, brings the activity cost to $96,891 ($59,100 + 7,791 + 30,000).

The remaining cost included in the activity Prepare Financial Statements is the Support cost. This is the cost of services provided by the human resources and information technology (IT) departments. The cost of activities such as Process Payroll, Provide IT Support, and Administer Compensation and Benefits are allocated to the other departments on the basis of headcount since, again, each employee has equal access to these services. Including this cost ($11,012) brings Prepare Financial Statements to the final value of $107,904.

The remaining activity costs for finance and the other departments were calculated in a similar manner.

Classifying Activities

When establishing the list of activities, the team classified them by their purpose. The main classifications or types of activities included Support, Product, Customer, and Business Sustaining. Classifying the activities helped the team develop the high-level ABC model shown in Fig. 3.6.3

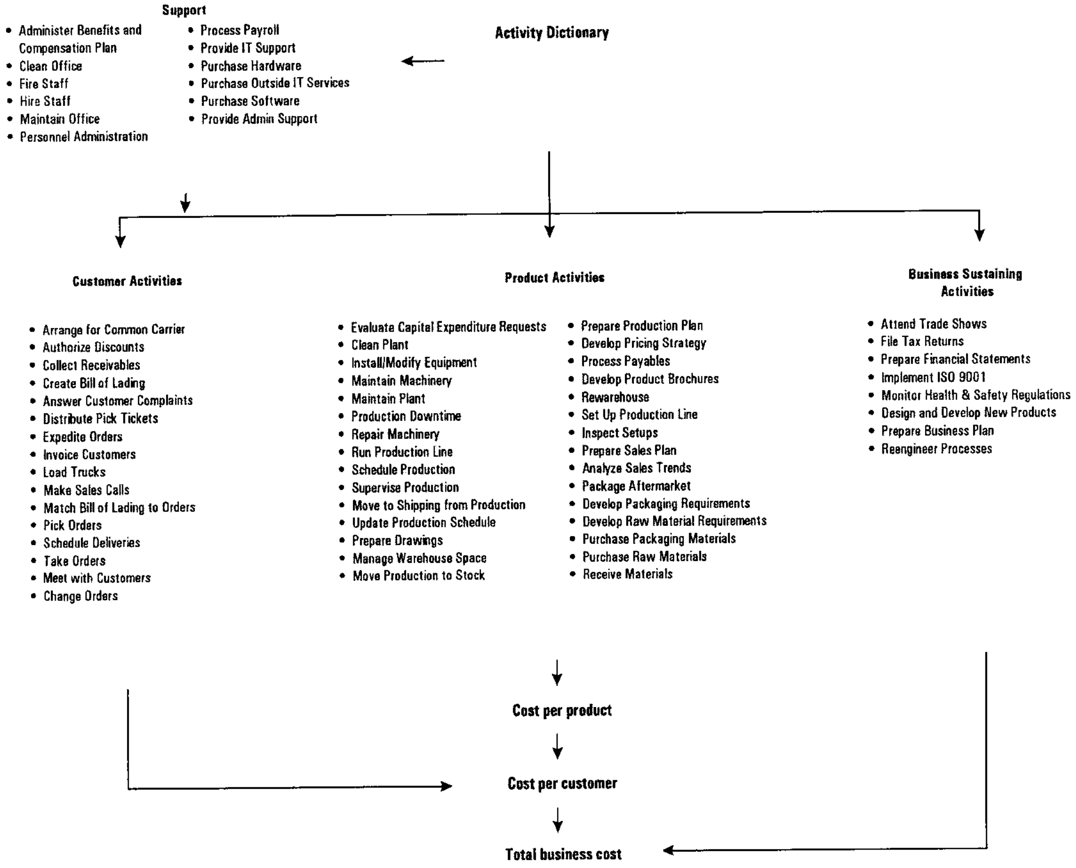
Support
• Administer Benefits and Compensation Plan
• Clean Office
• Fire Staff
• Hire Staff
• Maintain Office
• Personnel Administration
• Process Payroll
• Provide IT Support
• Purchase Hardware
• Purchase Outside IT Services
• Purchase Software
• Provide Admin Support
Activity Dictionary
Customer Activities
• Arrange for Common Carrier
• Authorize Discounts
• Collect Receivables
• Create Bill of Lading
• Answer Customer Complaints
• Distribute Pick Tickets
• Expedite Orders
• Invoice Customers
• Load Trucks
• Make Sales Calls
• Match Bill of Lading to Orders
• Pick Orders
• Schedule Deliveries
• Take Orders
• Meet with Customers
• Change Orders
Product Activities
• Evaluate Capital Expenditure Requests
• Clean Plant
• Install/Modify Equipment
• Maintain Machinery
• Maintain Plant
• Production Downtime
• Repair Machinery
• Run Production Line
• Schedule Production
• Supervise Production
• Move to Shipping from Production
• Update Production Schedule
• Prepare Drawings
• Manage Warehouse Space
• Move Production to Stock
• Prepare Production Plan
• Develop Pricing Strategy
• Process Payables
• Develop Product Brochures
• Rewarehouse
• Set Up Production Line
• Inspect Setups
• Prepare Sales Plan
• Analyze Sales Trends
• Package Aftermarket
• Develop Packaging Requirements
• Develop Raw Material Requirements
• Purchase Packaging Materials
• Purchase Raw Materials
• Receive Materials
Business Sustaining Activities
• Attend Trade Shows
• File Tax Returns
• Prepare Financial Statements
• Implement ISO 9001
• Monitor Health & Safety Regulations
• Design and Develop New Products
• Prepare Business Plan
• Reengineer Processes
Cost per product
Cost per customer
Total business cost

FIGURE 3.6.3 ABC model.

Support activities are those performed by the human resources and IT departments to provide a service to internal customers. An example of a support activity is Process Payroll. The cost of these activities are reallocated to the other activities.

The activities classified as Product, such as Purchase Raw Materials, Schedule Production, or Develop Product Brochures, are necessary to provide the product and are included in the product cost. The Customer activities, like Invoice Customers, do not help produce the product, but do service specific customers or customer groups. This cost is commonly referred to as the *cost to serve.* The cost per customer is determined by taking the cost of the products each customer purchases plus the cost to serve. The final activity type, Business Sustaining, includes those activities required by the firm to continue as a going concern but do not directly help service an internal customer, produce the products, or service external customers.

The total division costs are the sum of the Product, Customer, and Business Sustaining costs (the cost of the Support activities are included in the other activities). The bottom line is the same as in the income statement (Table 3.6.1). The difference is merely one of presentation.

Combining the costs with the relevant revenues allowed Jane to come up with profitability figures for products and customers. First, Jane developed the profitability figures for Auto Parts International's products.

Profitability by Product, Customer, and Division

The Brake Rotor Division produces four distinct products. However, because the products go to two different channels, each product has two product codes, one for each channel, for a total of eight. The OEM customer orders are produced on a make-to-order basis and shipped immediately while the aftermarket (AFM) orders are made to stock. A portion of all production runs for OEM orders are put aside for aftermarket orders. In addition, the aftermarket products require individual packaging, while the OEM products are shipped on skids with minimum packaging.

Product Profitability. Table 3.6.5 shows the activities designated Product and how their costs are distributed to the products on the basis of the cost drivers. The cost driver is the allocation basis for splitting the activity to the cost object (product, customer, etc.). For example, the cost driver for the activity Schedule Production is the number of production runs—150 for the year. Bill and the team felt that it took approximately the same amount of time to schedule each run, so the number of runs associated with each product was a good indication of how the activity was consumed. In this way they determined that $8,988 (48 of 150 runs × $28,086) was associated with the first brake rotor (BR1). The remaining product activity costs were determined in a similar manner. The figure first breaks down the costs common to both channels, then adds the channel-specific activities. Next, the material costs were included to obtain a total cost per product. Taking into account the production volume, which was assumed to be equal to the sales volume in this case, the cost per unit was determined. Including the revenue per product allowed the profitability per product to be calculated as well.

Jane and Bill were surprised to find that only the product codes OEMBR1, AFMBR1, and OEMBR2 made money. Frank, the KPMG consultant, commented that this was not all that surprising since ABC commonly reveals that the high-volume products are subsidizing the low-volume products. The team now had some new information to consider.

The results of the product analysis left the group anxious to look at the costs associated with Auto Parts International's customers. Table 3.6.6 shows the result of the investigation into customer costs.

Customer Profitability. The first step in determining customer profitability is to determine the profitability associated with the products each customer purchased. Table 3.6.6 shows the profitability per product and the units purchased by each customer, multiplying the two gives the total profitability of a product purchased. For example, National Motors purchased 300,000 OEMBR1 rotors at a profitability per unit of $4.45 for a total of $1,333,818.

The second part of customer costs (that is, cost to serve the customer) is calculated in a similar way to the product costs. The consumption of the drivers distributes the activity costs to the relevant customers. The sum of the profitability of the products purchased and the customer activity cost equals the total customer profitability.

Again, the team was surprised when they saw the results. The only profitable customer was National Motors. The other two OEMs were unprofitable, and at –$321,887, the distributors were losing the company money in a big way!

Divisional Profitability. Jane finished the exercise by developing a divisional income statement on an ABC basis, as shown in Table 3.6.7. As expected, the overall profitability determined using ABC methods is the same as that determined through traditional accounting methods. ABC does not add or subtract costs, but simply restates the numbers in different terms. However, the new information provided within the product and customer profitability analysis excited the team members, and they decided to present the information to the rest of the management team to determine how they could use it to improve the profitability of the business.

TABLE 3.6.5 Product Profitability

			Driver Consumption					Activity Cost Per Product			
Activity	Cost Driver	Activity Cost	BR1	BR2	BR3	BR4	Total	BR1	BR2	BR3	BR4
Analyze Sales Trends	# of Products	$84,597	1	1	1	1	4	$21,149	$21,149	$21,149	$21,149
Clean Plant	# of Production Line Hrs	74,700	3,402	815	1,101	702	6,020	42,214	10,113	13,662	8,711
Depreciation	# of Production Line Hrs	723,000	3,402	815	1,101	702	6,020	408,579	97,881	132,230	84,310
Develop Pricing Strategy	# of Products	63,235	1	1	1	1	4	15,809	15,809	15,809	15,809
Develop Raw Material Requirements	# of Products	10,677	1	1	1	1	4	2,669	2,669	2,669	2,669
Evaluate Capital Expenditure Requests	# of Production Line Hrs	60,472	3,402	815	1,101	702	6,020	34,174	8,187	11,060	7,052
Inspect Setups	# of Production Runs	76,975	48	36	42	24	150	24,632	18,474	21,553	12,316
Install/Modify Equipment	# of Production Line Hrs	99,337	3,402	815	1,101	702	6,020	56,137	13,448	18,168	11,584
Maintain Machinery	# of Production Line Hrs	80,746	3,402	815	1,101	702	6,020	45,631	10,932	14,768	9,416
Maintain Plant	# of Production Line Hrs	31,482	3,402	815	1,101	702	6,020	17,791	4,262	5,758	3,671
Move to Shipping from Production	Volume of Production	61,327	300,000	60,000	85,000	54,000	499,000	36,870	7,374	10,446	6,637
Prepare Drawings	# of Drawings	58,609	1	1	1	1	4	14,652	14,652	14,652	14,652
Prepare Production Plan	Volume of Production	54,489	330,000	66,190	93,510	60,300	550,000	32,693	6,557	9,264	5,974
Prepare Sales Plan	# of Products	35,029	1	1	1	1	4	8,757	8,757	8,757	8,757
Process Payables	# of Vouchers	55,869	48	36	42	24	150	17,878	13,408	15,643	8,939
Production Downtime	# of Production Line Hrs	479,221	3,402	815	1,101	702	6,020	270,816	64,878	87,645	55,883
Purchase Raw Materials	# of POS	14,779	48	36	42	24	150	4,729	3,547	4,138	2,365
Receive Materials	# of Receipts	88,560	48	36	42	24	150	28,339	21,254	24,797	14,170
Repair Machinery	# of Production Line Hrs	61,109	3,402	815	1,101	702	6,020	34,534	8,273	11,176	7,126
Run Production Line	# of Direct Labor Hrs	958,442	20,072	4,972	6,551	4,282	35,876	536,220	132,814	175,009	114,399
Schedule Production	# of Production Runs	28,086	48	36	42	24	150	8,988	6,741	7,864	4,494
Set Up Production Line	# of Production Runs	395,726	48	36	42	24	150	126,632	94,974	110,803	63,316

Supervise Production	# of Production Line Hrs	96,608	3,402	815	1,101	702	6,020	54,594	13,079	17,669	11,266
Update Production Schedule	# of Production Runs	24,699	48	36	42	24	150	7,904	5,928	6,916	3,952
Utilities	# of Production Line Hrs	123,000	3,402	815	1,101	702	6,020	69,509	16,652	22,496	14,343
Total		$3,840,773						$1,921,900	$621,814	$784,100	$512,958
Volume								330,000	66,190	93,510	60,300
Activity Cost Per Unit								$5.82	$9.39	$8.39	$8.51
Material Cost Per Unit								$5.23	$5.43	$6.54	$6.24
Total Cost Per OEM Unit								$11.05	$14.82	$14.93	$14.75
Price Per OEM Unit								$15.50	$16.00	$14.50	$14.50
Profit Per OEM Unit								$4.45	$1.18	($0.43)	($0.25)
Develop Packaging Requirements	# of Products	5,660	1	1	1	1	4	1,415	1,415	1,415	1,415
Manage Warehouse Space	Avg Volume in Stock	16,583	2,500	1,032	1,702	1,050	6,284	6,598	2,723	4,492	2,771
Move Production to Stock	# of Stocks	55,244	30,000	6,190	8,510	6,300	51,000	32,497	6,705	9,218	6,824
Package Aftermarket	AFM Production	126,760	30,000	6,190	8,510	6,300	51,000	74,565	15,385	21,152	15,659
Develop Product Brochures	# of Brochures	94,890	1	1	1	1	4	23,723	23,723	23,723	23,723
Rewarehouse	Avg Volume in Stock	54,665	2,500	1,032	1,702	1,050	6,284	21,749	8,975	14,807	9,135
Purchase Packaging Materials	# of Pkg POS	12,111	12	4	4	4	24	6,055	2,018	2,018	2,018
Total		$365,914						$166,601	$60,944	$76,824	$61,544
Volume								30,000	6,190	8,510	6,300
Activity Cost Per Unit								$5.55	$9.85	$9.03	$9.77
Packaging Cost Per Unit								$1.76	$1.54	$1.98	$1.65
Total Cost Aftermarket Product (AFM)								$18.37	$26.21	$25.93	$26.17
Price Per Aftermarket Unit (AFM)								$23.25	$24.00	$21.75	$21.75
Profit Per Aftermarket Unit (AFM)								$4.88	($2.21)	($4.18)	($4.42)

TABLE 3.6.6

			Units Sold				Profit of Products			
Product	Profit Per Unit	Total Volume	National Motors	Tokyo Auto-motive	Rhine-land Motors	Distributors	National Motors	Tokyo Auto-motive	Rhine-land Motors	Distributors
OEMBR1	$4.45	300,000	300,000				$1,333,818			
OEMBR2	$1.18	60,000	60,000				70,537			
OEMBR3	($0.43)	85,000		85,000				($36,142)		
OEMBR4	($0.25)	54,000			54,000				($13,326)	
AFMBR1	$4.88	30,000				30,000				$146,481
AFMBR2	($2.21)	6,190				6,190				(13,680)
AFMBR3	($4.18)	8,510				8,510				(35,595)
AFMBR4	($4.42)	6,300				6,300				(27,819)
Total Cost of Products Purchased		550,000					1,404,355	(36,142)	(13,326)	69,387

				Cost Driver Consumption				Activity Cost			
Activity	Cost Driver	Activity Cost	Total Driver Qty	National Motors	Tokyo Auto-motive	Rhine-land Motors	Distributors	National Motors	Tokyo Auto-motive	Rhine-land Motors	Distributors
Arrange for Common Carrier	# of Shipments	$16,583	285	20	15	35	215	$1,164	$873	$2,037	$12,510
Authorize Discounts	# of Orders	19,531	235				235				19,531
Change Orders	# of Changes	20,034	49	3	10	4	32	1,227	4,088	1,635	13,083
Collect Receivables	# of Overdue	95,893	34				34				95,893
Create Bill of Lading	# of BOLs	39,050	1247	535	170	108	434	16,754	5,324	3,382	13,591
Answer Customer Complaints	# of Complaints	35,450	100%	10%	20%	30%	40%	3,545	7,090	10,635	14,180
Distribute Pick Tickets	# of Pick Tickets	8,291	434				434				8,291
Expedite Orders	# of Expedited	30,425	49	3	10	4	32	1,863	6,209	2,484	19,869
Invoice Customers	# of Invoices	25,042	262	12	12	8	230	1,147	1,147	765	21,983
Meet with Customers	Time Spent	116,475	100%	45%	20%	25%	10%	52,414	23,295	29,119	11,647
Load Trucks	# of Shipments	46,374	1247	535	170	108	434	19,896	6,322	4,016	16,140
Make Sales Calls	Time Spent	269,706	100%	50%	20%	20%	10%	134,853	53,941	53,941	26,971
Match Bill of Lading to Orders	# of BOLs	24,329	1247	535	170	108	434	10,438	3,317	2,107	8,467
Pick Orders	# of Orders	61,832	434				434				61,832
Schedule Deliveries	# of Shipments	8,291	1247	535	170	108	434	3,557	1,130	718	2,886
Take Orders	# of Orders	48,676	569	28	14	8	519	2,395	1,198	684	44,398
Total		$865,983						249,252	113,934	111,523	391,274
Customer Profit								$1,155,104	($150,076)	($124,849)	($321,887)

TABLE 3.6.7 ABC Income Statement

Total Profitability		
Revenue		$8,793,678
Total Product Costs	7,369,403	
Customer Activity Costs	865,983	
Total Customer Costs		8,235,385
Business Sustaining Activities		
Attend Trade Shows	130,339	
File Tax Returns	22,388	
Prepare Financial Statements	107,904	
Implement ISO 9001	58,111	
Monitor Health & Safety Regulations	14,149	
Design and Develop New Products	41,928	
Prepare Business Plan	92,505	
Reengineer Processes	53,757	
		521,081
Gross Profit		$37,211

THE PROCESS VIEW—ACTIVITY-BASED MANAGEMENT

ABC is a well-known method for developing more accurate product costs. But, over the years, ABC has come to include both the cost assignment view (original ABC) and the process views as shown in Fig. 3.6.4. In the cost assignment view, resources are traced to activities; then activities are traced to cost objects.

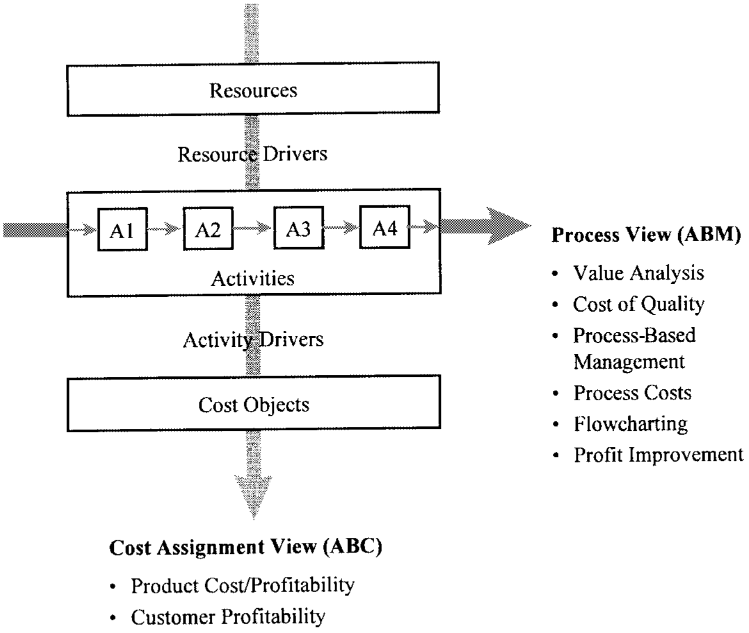
Resources
Resource Drivers
A1
A2
A3
A4
Activities
Activity Drivers
Cost Objects
Process View (ABM)
• Value Analysis
• Cost of Quality
• Process-Based Management
• Process Costs
• Flowcharting
• Profit Improvement
Cost Assignment View (ABC)
• Product Cost/Profitability
• Customer Profitability

FIGURE 3.6.4 Cost assignment view versus process view.

As shown in the Auto Parts International example, the cost assignment view has expanded from the original product costing exercises to include other cost objects such as customers. In other applications, cost objects could include channels of distribution, suppliers, work orders, projects, and others of economic interest. In the most comprehensive applications, ABC concepts are used to develop an enterprise model that takes into account all of an organization's revenues and expenditures. The first part of the case demonstrates that an enterprise model provides management with a thorough understanding of both product and customer profitability.

Although this information provides two major building blocks in developing an in-depth understanding of a company's economics, knowledge of the company's processes is also beneficial. A process is, after all, just a series of activities. Eventually companies found that not only is ABC a great tool for providing better costing information but the activity information is useful for analyzing processes as well. This led to the development of the process view, or activity-based management (ABM), which focuses on managing the company's activities and improving profit.

Early sales pitches for ABC suggested that unprofitable products would be uncovered and deleted from the product list, allowing the firm to move to a higher level of profitability. In most cases, this did not occur: The products, even though unprofitable, were contributing to covering the fixed costs. At the very least, before dropping products, firms felt obligated to try to improve the economics. The focus of ABC over the years has shifted to profit improvement from simply conducting costing exercises. The next sections of the case: Activity Analysis and Process Costs will highlight techniques employed by ABM to accomplish profit improvement.

ACTIVITY ANALYSIS

Activities That Add Value

In discussions with the management team, Frank raised the point that many firms he had worked with previously had benefited from what he called an *attribute analysis.* One type of attribute analysis that the management team got quite excited about was a *value analysis.* The purpose of this analysis was to determine which activities added value, and which did not. Frank said that the best test of whether an activity was value-added was to ask this question, "If a customer knew you were doing this activity, would they pay for it?"

Management assessed each activity on its perceived value (value-added versus non-value-added) to the organization. While the assignment of activities to the different classifications was highly subjective, management easily reached a consensus on the rankings.

When Ted, the vice president of finance, saw the results, he said, "If we can redirect the resources involved in the non-value-added activities to other more productive ones, we will have saved the firm up to $644,574":

Answer Customer Complaints	$35,540
Change Orders	20,034
Update Production Schedule	24,699
Expedite Orders	30,425
Rewarehouse Product	54,665
Production Downtime	479,211
Total	$644,574

The management team agreed to take a closer look at these activities and develop a plan to eliminate or, at the very least, reduce them.

Jeremiah, the president, commented that he was very happy to see that ABC was already providing a payback, and told the team to keep up the good work.

Other Attribute Analyses

Besides the value analysis, Frank suggested other attribute analyses were possible:

- Cost of quality
- Touch time
- Efficiency
- Effectiveness
- Primary versus secondary

The cost of quality caught Bill's attention: The Brake Rotor Division had been implementing ISO 9001, and were planning to monitor the cost of quality. Figure 3.6.5 shows the parameters used to define the cost of quality (COQ).

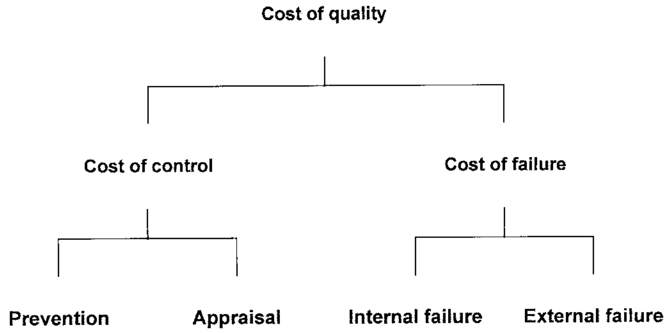

FIGURE 3.6.5 Cost of quality.

The internal and external failure costs both result from the product not meeting quality standards, either by not performing properly in-house before shipment or later in the customer's hands. This is the most costly type of breakdown, since there are costs beyond the immediate activity costs—such as reworking the product to proper specifications or replacing it. In particular, external failure can result in future loss of business or loss of customer goodwill.

Theoretically, the only acceptable expenses for COQ are prevention costs.

Attempting to eliminate or at least minimize the other costs should be one of management's goals and, as we have been told, you can't manage what you don't measure. By attaching the relevant activities (not all activities are costs of quality) to the appropriate section of the hierarchy, it is possible to measure and begin to manage the cost of quality.

After inspecting the activity dictionary and using his industrial engineering labor analysis skills, Bill concluded that many of the activities associated with COQ were not identified. While some activities were clearly a cost of quality such as Inspect Setups, others such as Rework Product were missing. The team agreed that the next iteration of the model would identify all costs of quality rather than leaving them buried in the other activities.

TABLE 3.6.8 Process Costs by Department ($)

Process	Activity	Customer Service	Executive	Finance
Acquire Materials	Develop Packaging Rqts	0	0	0
	Develop Raw Material Rqts	0	0	0
	Process Payables	0	0	55,869
	Purchase Packaging Materials	0	0	4,221
	Purchase Raw Materials	0	0	6,332
	Receive Materials	0	0	0
Acquire Materials Total		0	0	66,421
Fill Customer Orders	Arrange for Common Carrier	0	0	0
	Change Orders	20,034	0	0
	Collect Receivables	0	0	95,893
	Create Bill of Lading	39,050	0	0
	Distribute Pick Tickets	0	0	0
	Expedite Orders	0	0	0
	Invoice Customers	25,042	0	0
	Load Trucks	0	0	0
	Manage Warehouse Space	0	0	0
	Match Bill of Lading to Orders	0	0	0
	Move Production to Stock	0	0	0
	Move to Shipping	0	0	0
	Package Aftermarket	0	0	0
	Pick Orders	0	0	0
	Rewarehouse	0	0	0
	Schedule Deliveries	0	0	0
	Take Orders	48,676	0	0
Fill Customer Orders Total		132,802	0	95,893
Manufacture Product	Inspect Setups	0	0	0
	Production Downtime	0	0	0
	Run Production Line	0	0	0
	Schedule Production	0	0	0
	Set Up Production Line	0	0	0
	Supervise Production	0	0	0
	Update Production Schedule	0	0	0
Total		0	0	0
	Prepare Business Plan	0	38,327	25,905
	Prepare Production Plan	0	0	0
	Prepare Sales Plan	0	0	0
Total		0	38,327	25,905
Provide Fin/Admin Support	File Tax Returns	0	0	22,388
	Prepare Financial Statements	0	0	107,904
Provide Fin/Admin Support Total		0	0	130,292
Provide Manufacturing Support	Clean Plant	0	0	0
	Depreciation	0	0	0
	Design/Develop New Products	0	19,163	0
	Evaluate Cap Exp Requests	0	9,582	8,235
	Implement ISO 9001	0	9,582	0

CASE STUDY: IMPLEMENTING AN ACTIVITY-BASED COSTING PROGRAM AT AUTO PARTS INTERNATIONAL

Department								
Industrial Engineering	Mainten-ance	Marketing	Plant Management	Production	Quality Assurance	Sales	Shipping Receiving	Grand Total
0	0	0	0	5,660	0	0	0	5,660
0	0	0	0	10,677	0	0	0	10,677
0	0	0	0	0	0	0	0	55,869
0	0	0	0	7,890	0	0	0	12,111
0	0	0	0	8,447	0	0	0	14,779
0	0	0	0	0	26,729	0	61,832	88,560
0	0	0	0	32,673	26,729	0	61,832	187,655
0	0	0	0	0	0	0	16,583	16,583
0	0	0	0	0	0	0	0	20,034
0	0	0	0	0	0	0	0	95,893
0	0	0	0	0	0	0	0	39,050
0	0	0	0	0	0	0	8,291	8,291
0	0	0	5,551	0	0	0	24,874	30,425
0	0	0	0	0	0	0	0	25,042
0	0	0	0	0	0	0	46,374	46,374
0	0	0	0	0	0	0	16,583	16,583
0	0	0	0	0	24,329	0	0	24,329
0	0	0	0	0	24,329	0	30,916	55,244
0	0	0	0	0	30,411	0	30,916	61,327
0	0	0	0	95,844	0	0	30,916	126,760
0	0	0	0	0	0	0	61,832	61,832
0	0	0	0	0	0	0	54,665	54,665
0	0	0	0	0	0	0	8,291	8,291
0	0	0	0	0	0	0	0	48,676
0	0	0	5,551	95,844	79,068	0	330,242	739,399
0	0	0	0	0	76,975	0	0	76,975
0	0	0	0	479,221	0	0	0	479,221
0	0	0	0	958,442	0	0	0	958,442
0	0	0	0	28,086	0	0	0	28,086
0	0	0	0	395,726	0	0	0	395,726
0	0	0	0	96,608	0	0	0	96,608
0	0	0	0	24,699	0	0	0	24,699
0	0	0	0	1,982,782	76,975	0	0	2,059,757
	0	8,062	11,101	3,987	0	0	0	92,505
0	0	0	22,203	32,286	0	0	0	54,489
0	0	0	0	0	0	35,029	0	35,029
	0	8,062	33,304	36,273	0	35,029	0	182,023
0	0	0	0	0	0	0	0	22,388
0	0	0	0	0	0	0	0	107,904
0	0	0	0	0	0	0	0	130,292
0	74,700	0	0	0	0	0	0	74,700
0	0	0	723,000	0	0	0	0	723,000
17,214	0	0	5,551	0	0	0	0	41,928
37,105	0	0	5,551	0	0	0	0	60,472
17,491	0	0	5,551	0	25,487	0	0	58,111

TABLE 3.6.8 Process Costs by Department ($) (*Continued*)

Process	Activity	Customer Service	Executive	Finance
	Install/Modify Equipment	0	0	0
	Maintain Machinery	0	0	0
	Maintain Plant	0	0	0
	Monitor Health & Safety	0	0	0
	Prepare Drawings	0	0	0
	Reengineer Processes	0	0	0
	Repair Machinery	0	0	0
	Utilities	0	0	0
Provide Manufacturing Support Total		0	38,327	8,235
Sell and Market Product	Analyze Sales Trends	0	19,163	23,505
	Answer Customer Complaints	35,450	0	0
	Attend Trade Shows	0	21,563	11,118
	Authorize Discounts	0	0	0
	Develop Pricing Strategy	0	19,163	0
	Develop Product Brochures	0	9,582	0
	Meet with Customers	0	47,927	0
	Make Sales Calls	0	0	0
Sell and Market Product Total		35,450	117,399	34,623
Grand Total		168,252	194,053	361,369

Frank commented that because ABC is more art than science, it usually takes a couple of iterations to adequately model costs. Since the team did not define the requirement for COQ at the beginning of the project, he said that he was not surprised at this outcome. Bill tasked himself to develop a list of activities he believed should be included in the next ABC model as a COQ.

PROCESS COST

Mapping the Activities to the Processes

In addition to being able to model product and customer costs, ABC is also useful for modeling processes. When developing the activity dictionary, the project team also asked the management group to define the processes of the division. The management team came up with the following list:

- Plan Business
- Acquire Materials
- Sell and Market Product
- Manufacture Product
- Fill Customer Orders
- Provide Financial/Administrative Support
- Provide Manufacturing Support

By mapping the activities to the processes, the process costs by department were determined as shown in Table 3.6.8. As you can see, the original amount in the divisional income

Department								
Industrial Engineering	Maintenance	Marketing	Plant Management	Production	Quality Assurance	Sales	Shipping Receiving	Grand Total
24,736	74,600	0	0	0	0	0	0	99,337
0	80,746	0	0	0	0	0	0	80,746
0	31,482	0	0	0	0	0	0	31,482
0	0	0	0	14,149	0	0	0	14,149
58,609	0	0	0	0	0	0	0	58,609
37,105	0	0	16,652	0	0	0	0	53,757
0	61,109	0	0	0	0	0	0	61,109
0	0	0	123,000	0	0	0	0	123,000
192,259	322,637	0	879,304	14,149	25,487	0	0	1,480,399
0	0	0	0	0	0	41,929	0	84,597
0	0	0	0	0	0	0	0	35,450
19,501	0	10,862	12,001	0	0	55,294	0	130,339
0	0	0	0	0	0	19,531	0	19,531
0	0	16,123	5,551	0	0	22,397	0	63,235
0	0	85,309	0	0	0	0	0	94,890
25,181	0	9,262	3,600	0	30,505	0	0	116,475
0	0	0	0	0	0	269,706	0	269,706
44,682	0	121,556	21,152	0	30,505	408,858	0	814,225
242,064	322,637	129,617	939,311	2,161,723	238,764	443,887	392,073	5,593,750

statement of $5,593,750 (includes departmental expense of $3,955,750 and the direct labor cost of $1,638,000, but does not include material costs) has been broken down into activity and process costs. Similar to the cost assignment view example, no additional costs have been added, nor have any been taken away—the accounts have simply been restated in a different manner.

Process-based Management

Tom Hayes, the general manager of the division, was excited when he saw the information. Tom was new to the firm and perceived a lack of cooperation between the different departments. Tom believed this information gave him insight into how to break down the departmental silos. Tom had heard about process-based management at a conference he had attended a couple of months ago. To facilitate better management, Tom decided to organize on a process basis as well as the functional basis. Because processes such as Fill Customer Orders cross different functional areas, employees are potentially members of several process teams—leaders on some, followers on others. The ABC analysis made it clear who performed which activities, and which team(s) each person should be on. Tom told the project team that he would name process leaders at the next management meeting.

Profitability Improvement

Beyond looking at the magnitude of the processes and their cross-departmental nature, the management team thought an in-depth analysis of several of the processes would lead to greater profitability.

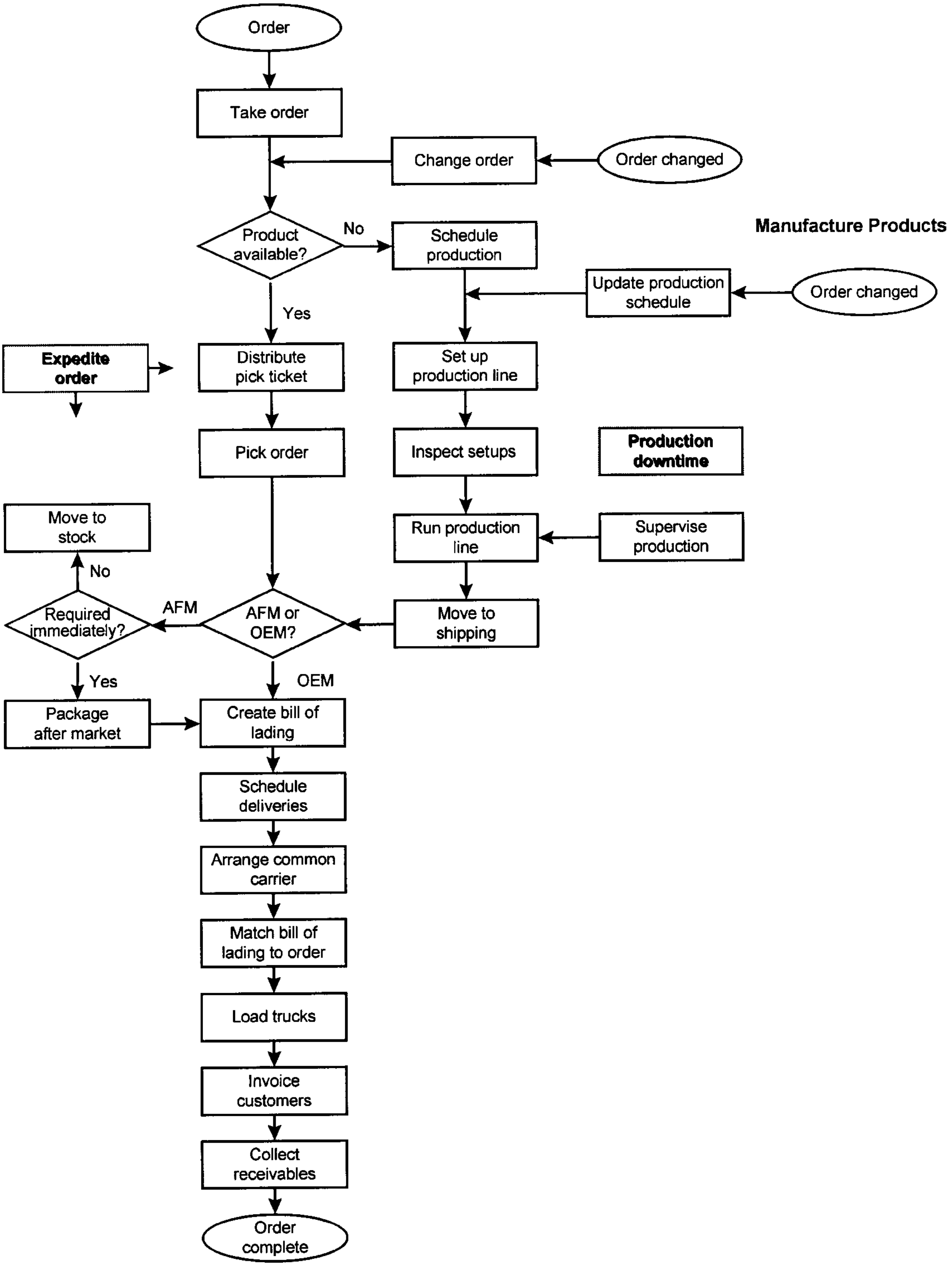
Order
Take order
Change order
Order changed
Manufacture Products
Product available?
No
Schedule production
Update production schedule
Order changed
Yes
Expedite order
Distribute pick ticket
Set up production line
Pick order
Inspect setups
Production downtime
Move to stock
Run production line
Supervise production
No
AFM
Required immediately?
AFM or OEM?
Move to shipping
Yes
OEM
Package after market
Create bill of lading
Schedule deliveries
Arrange common carrier
Match bill of lading to order
Load trucks
Invoice customers
Collect receivables
Order complete

FIGURE 3.6.6 Fill customer order/manufacture product.

Morley Wells, the sales manager, reminded everyone that a key customer, one of the larger distributors, had been demanding better prices. At present, the distributors were losing a lot of money, according to the customer profitability analysis. While the aftermarket channel made a profit of $69,387 (see Table 3.6.6) before the cost to serve, the additional cost to serve cost of $391,274 put the distributors at a loss of $321,887. The team examined these activities and concluded that there were indeed several opportunities to reduce costs. However, almost all the cost to serve activities had to be eliminated for this channel to become profitable.

Morley commented that several of these activities were critical for success in this channel and couldn't be eliminated.

Bill suggested that the group take a step back and look at the whole process for providing the product, and he developed the flowcharts for the Fill Customer Orders and Manufacture Products processes shown in Fig. 3.6.6.

The most obvious opportunities for reducing costs were those identified in the value analysis, especially the production downtime costing $479,211. On further inspection, Bill had determined that "on paper" the division didn't require its second shift. Production runs could be completed within one shift if the setups were done on the afternoon shift. If this could be accomplished, a good deal of the production downtime could be eliminated. Bill took it upon himself to investigate further.

While the team did not find the "big score" to automatically save the company zillions, they believed that ABC was a great tool for identifying saving opportunities. Tom commented that he now had a much better understanding of the economics of the business. He believed that the ABC project would allow them to reduce at least a half-million dollars from their cost structure over the next year.

CONCLUSIONS

At a recent board of directors meeting, the chairman made a point of praising the work of the ABC implementation team. He noted that the ABC approach had resulted in a great improvement in decision support information. Also, the company's continuous improvement program was enhanced because the ABC results were now available to project team members. The board believed the ABC information was key to Auto Parts International reaching new levels of profitability.

Bill Burley returned to his industrial engineering duties with a strong feeling of accomplishment. Through the application of ABC, he was able to prove what he had really known all along—there is a better way to develop appropriate management cost information.

FURTHER READING

Cokins, Gary, "Activity-Based Cost Management—Making It Work," Irwin Professional Publishing, 1996. (book)

Kaplan, Robert S. and Robin Cooper, "Cost & Effect," Harvard Business School Press, 1998. (book)

BIOGRAPHIES

Brian Bush, P. Eng. is a management consultant with KPMG based in Waterloo, Ontario, Canada. His consulting career spans 18 years and he presently directs KPMG's industrial engineering practice. Prior to consulting, he held positions in industry as an industrial engineer and plant manager. He holds a B.A. Sc. (mechanical engineering) and an M.B.A. from the University of Toronto. He is a Certified Management Consultant (CMC) and a senior member of the Institute of Industrial Engineers (IIE). He is currently a member of the board of directors and is past president of the Toronto Chapter of the IIE.

Mike Senyshen is a management consultant with the Business Transformation Services Group of KPMG's Toronto, Ontario, Canada office. For the last five years he has specialized in implementing cost systems in manufacturing and logistics environments. Prior to joining KPMG, he was employed for seven years by Cadbury Beverages Canada where he was involved in financial planning, controllership, and systems development. He holds an M.B.A. from Queen's University, is a Certified General Accountant (CGA), and has completed his CPIM (Certification in Production and Inventory Management).

SECTION 4

WORK ANALYSIS AND DESIGN

CHAPTER 4.1

METHODS ENGINEERING AND WORKPLACE DESIGN

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Methods engineering is a systematic technique for the design and improvement of work methods. It provides a unified and thorough system for (a) analyzing the present work situation, identifying problems, bringing out improvement ideas, and selecting the best of those, and then (b) after implementation of improvements, standardizing the new methods, insuring their adoption, and measuring and evaluating their impact. Application of methods engineering has expanded to include indirect work, office work, and service work and the approach has shifted to the design of new work systems that did not previously exist. Likewise, the ultimate objectives for the application of methods engineering have broadened to include such objectives as balance between operator and work system from an ergonomic viewpoint and the adaptation of the work system to the environment from an ecological viewpoint.

Here, we introduce both the orthodox technique of methods engineering and its most recent refinement, the design approach, and discuss the future direction this technique is likely to take.

BACKGROUND

Methods engineering is a systematic technique for the design and improvement of work methods, for the introduction of those methods into the work place, and for ensuring their solid adoption. Methods engineering is one of the two basic industrial engineering (IE) techniques, the other being work measurement. In fact, these two were the starting point of IE and have been thoroughly researched and widely applied since the days of Frederick W. Taylor, Frank B. Gilbreth, and Lillian M. Gilbreth. Later, the various IE techniques were continually refined and the range of their application broadly expanded. And, as part of that trend, the

METHODS ENGINEERING AND WORKPLACE DESIGN

two main IE techniques were also changed and continually refined. Nevertheless, they continue to hold their key position as the two core technologies of IE. Methods engineering provides a unified and thorough system for (a) analyzing the present work situation, identifying problems, bringing out improvement ideas, and selecting the best of those, and then (b) after implementation of improvements, standardizing the new methods, insuring their adoption, and measuring and evaluating their impact. As such, methods engineering has historically provided a backbone for the advancement of IE, and other IE techniques have broadened the range of the application of methods engineering and led to its further development and refinement.

In the past, methods engineering focused on manufacturing processes and operations as the main target for improvement, but in recent years its scope has been increased to include indirect work, office work, and service work. Similarly, in the past the main approach was improvement of the *existing* work system, but recently, application of methods engineering has shifted to the design of *new* work systems that did not previously exist. Likewise, the ultimate objective behind design and improvement of work systems through the application of methods engineering has also broadened. Whereas in the past the objective was the improvement of labor productivity, today such objectives as balance between operator and work system from an ergonomic viewpoint and the adaptation of the work system to the environment from an ecological viewpoint are becoming important.

THE POSITION OF METHODS ENGINEERING

After F. W. Taylor first introduced time study, it developed in the direction of establishing standard times. Likewise, motion study, developed by Frank and Lillian Gilbreth, evolved into a technique for improving work methods. Eventually, the two techniques of time study and motion study were integrated and refined into a widely accepted method applicable to the improvement and upgrading of work systems. This integrated approach to work system improvement is known as methods engineering, and from the standpoint of content it is quite similar to work study, work simplification, and method study.

In the first days of methods engineering, the objective was improvement of existing work systems, but later a more design-oriented approach began to be adopted which could be applied even to the situation of developing and designing a completely new work system that had not existed before. In considering the *type of work system* being studied for improvement or design, the initial focus was on the improvement of systems composed mostly of individual work with a high content of repetitive operations. Later, the objective turned to design and/or improvement of complex work systems involving large numbers of people and equipment. At this time, the application of methods engineering has extended to the design and improvement in situations where large and complex systems, each involving numerous related activities, interact. In fact, the techniques of methods engineering are even being applied in business process reengineering (BPR).

With regard to the *types of operations* addressed, in the early days the focus was on manufacturing operations, particularly fabrication operations. Now, however, the focus has been extended to indirect operations peripheral to manufacturing, such as design, material handling, inspection, shipping, and maintenance, and even to indirect overhead areas of the enterprise, such as office work. Even in regard to the *industries* addressed, the application of methods engineering has expanded. It is no longer limited to use in manufacturing, but has been successfully applied to a variety of work systems involving the activities of people, in such organizations as service industries, hospitals, government offices, utilities, and distribution facilities.

The objectives of methods engineering have also gone through some changes. Originally limited to the simple objective of increasing labor productivity, methods engineering is now applied with the purpose of improving work system flexibility, expandability, and maintainability. It has even been used to create work systems whose objectives are improved customer satisfaction or greater ease and comfort for the operator—e.g., through enhanced ergonomics, improved safety, and a more comfortable work environment.

The technology used in performing methods engineering has also evolved. For example, the trend toward greater functionality and performance of computers at an ever-lower price has enabled the practical use of large-scale simulations and made it possible to evaluate precisely the functioning of newly designed systems. In addition, advances in software for spreadsheets, charting, data gathering, analysis, and presentations have given the average user tools that previously could only be used by experts. Computer-aided design (CAD) software makes it simple to create, edit, and revise the drawings needed for plan design. Similarly, the use of video camera-recorders (VCRs) for time studies has greatly reduced the amount of time needed to become skillful in measurement techniques and even users with limited training can readily take effective measurements.

THE DEFINITION OF METHODS ENGINEERING

Although we readily speak of "methods engineering," there are actually a variety of definitions. In this article, we will use the following classical definition, which appears in the 3rd edition of the *Industrial Engineering Handbook* [1]:

> The technique that subjects each operation of a given piece of work to close analysis to eliminate every unnecessary element or operation and to approach the quickest and best method of performing each necessary element or operation. It includes the improvement and standardization of methods, equipment, and working conditions: operator training; the determination of standard time; and occasionally devising and administering various incentive plans.

This definition, however, tends to define methods engineering rather narrowly. It states that methods engineering is limited to operations or pieces of work, but recently the trend has been to address broader areas, such as production processes, the factory in total, or large scale work systems that involve a lot of people and extensive equipment. And we agree that these also are proper target areas for the application of methods engineering.

STEPS IN PERFORMING METHODS ENGINEERING

When making improvements or designs by the means of methods engineering, it is best to perform the necessary actions following a set procedure. This procedure should be made clear prior to starting actual activities, as that will result in the following benefits:

- It is possible ahead of time to get a good understanding among all the people involved.
- Improvement activities will be more efficient and wasted effort can be avoided.
- By concentrating on the step at hand, the quality of work done for each step will increase.
- Monitoring of progress can be readily done.

The procedures for methods engineering have essentially been formalized. (See Fig. 4.1.1.) In the following we have explained the methods engineering procedure for a manufacturing operation and have also introduced topics related to each step. When this procedure is applied to a business operation other than manufacturing, only the content of the analytical techniques changes; the implementation steps themselves remain the same.

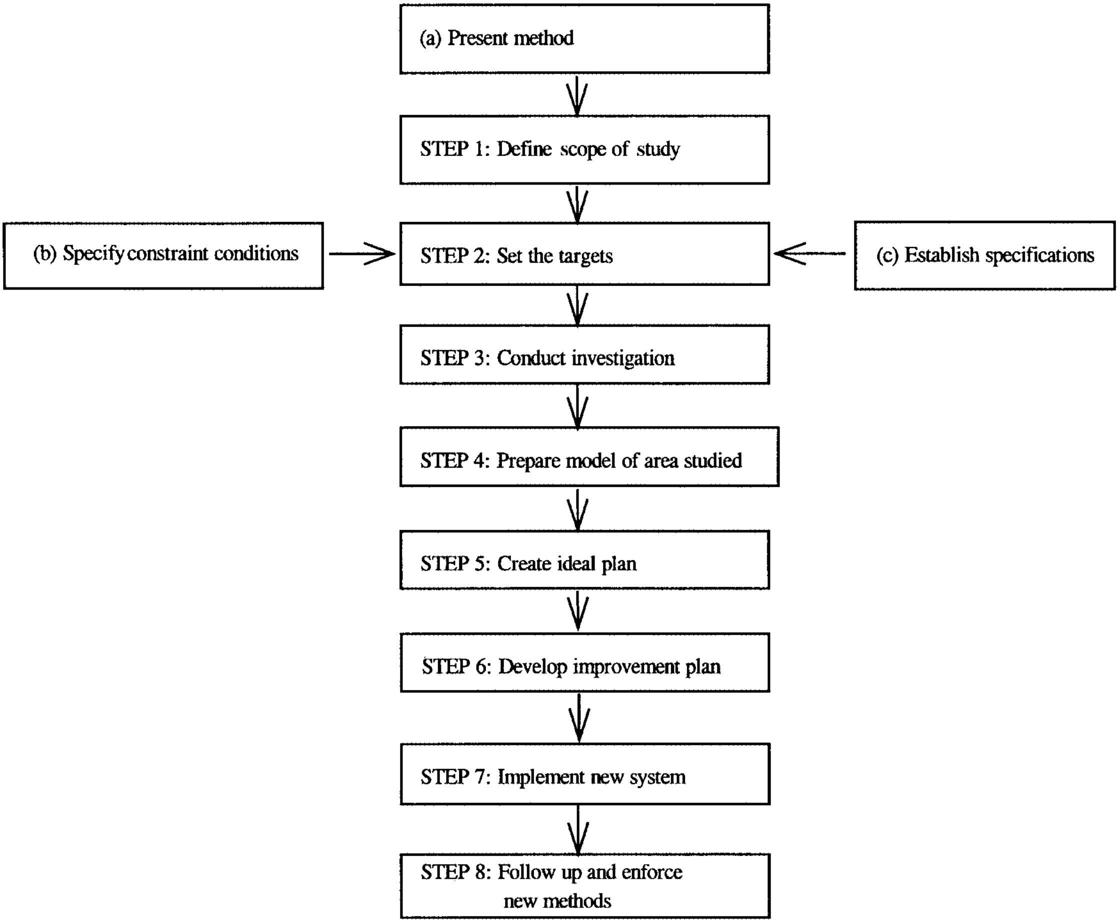
(a) Present method
STEP 1: Define scope of study
(b) Specify constraint conditions
STEP 2: Set the targets
(c) Establish specifications
STEP 3: Conduct investigation
STEP 4: Prepare model of area studied
STEP 5: Create ideal plan
STEP 6: Develop improvement plan
STEP 7: Implement new system
STEP 8: Follow up and enforce new methods

FIGURE 4.1.1 Procedure for methods engineering (analytical approach).

Step 1: Defining the Scope of the Study

Step 1 of the methods engineering procedure is (a) to decide what is to be improved, or in other words, to select the *kaizen* goal and (b) to select the study scope—the problem that must be solved or the bottleneck that must be removed in order to achieve the desired improvement. (Note: Instead of the word *improvement,* which is used so broadly in English, we have used the Japanese word *kaizen.* This is not to imply association with any particular school of *kaizen,* but simply to convey a specialized use of the term improvement—i.e., "a systematic approach to improvements in business systems"—which most English speakers will recognize in the word *kaizen.*)

In the case of manufacturing operations, typical goals are: improvement of labor productivity, improvement of equipment productivity, reduction of inventory in the factory, and establishment of measures to deal efficiently with a broad variety of products. In other types of operations, in addition to productivity improvement, the goals often include: reduction of business process lead times, reduction or elimination of customer waiting time, smoothing of peak loads for business processes, etc. And, as mentioned previously, recently some new goals are: improvement of the ergonomic aspects of the workplace, balancing of the work system with the work environment, and ecological factors.

Once the improvement (*kaizen*) goal has been decided on, selection of the area to be studied is addressed. The area chosen as the target, or subject matter, of the study (such as a department in the company, a production line, a process in a complex manufacturing operation, etc.) is called simply the *study subject.* In deciding which process in the system to select as the study subject, we consider "*kaizen* effectiveness" and try to select the subject that, if improved, will have the greatest effect on the system in terms of augmenting the chosen goal. In some cases, the problem areas will be obvious to all concerned and there will be no difficulty in selecting the study subject. In other cases, it may not be clear where the problems lie and it will be difficult to choose a single study subject. For example, modern work systems often involve many interrelated elements, and it is not easy to judge which area has the biggest problems. Yet, in order to achieve the maximum result with limited investment of funds and human resources, it is essential to select as the study subject a process that is the bottleneck for the entire operation. In such a case, it may be necessary to conduct a preliminary investigation in order to reveal where problems lie and which process is the main bottleneck. By conducting such a preliminary investigation, it will be possible not only to select the most appropriate study subject, but also to accurately estimate the improvement likely to result from the *kaizen* activity. The amount of resources (funds and human resources) that will have to be allocated to the activity can be estimated and realistic mid-range and long-range schedules for the improvement activities can be created.

In determining the study subjects for the preliminary investigation, the IE analytical methods used in Step 3 are often applied. It is, however, important to simplify both the analysis and the investigation based on the nature of the problems and the improvements that will ultimately be made. In the preliminary investigation, rather than a minute and precise analysis, a speedy and all-encompassing analysis should be performed.

Step 2: Setting the Goal to Be Achieved and the Project Specification

Step 2 in methods engineering is to set the goal to be achieved and to create the project specification. To do this, first, general data concerning the improvement target (study subject) is collected. If the subject is within a factory, this data will include such things as past production volume, allocated personnel, the items produced, the equipment and materials used, and the variety of finished products produced.

In addition, any constraints on the improvement activities should be clarified. By making such constraints clear ahead of time, the wasted effort of creating alternatives that could not be implemented anyway can be avoided. Constraints may include an upper limit on cost, the time allowed for the improvement activities, and the range within which changes could be made to the facilities and buildings used.

The design specifications are also clarified during this step. Design parameters may include processing (production) capacity, the products to be handled, the throughput time, and quality standards.

Within the limits of the constraints and specifications which have been clarified in this way, the goal to be achieved is set. This goal is established based on the results of the preliminary investigation.

Step 3: Doing the Analysis

When the project goal is improvement or redesign of an existing work system, that work system must first be analyzed and its current conditions accurately understood. In doing the analysis, the following points are important.

- Take a quantitative approach as much as possible.
- Analyze to a level of preciseness adapted to the subject being analyzed (not too coarse, not too detailed).
- Present results visually (make good use of charts, graphs, and drawings).

A variety of techniques for analysis and charting have for a long time been established as IE techniques. Among the methods of analysis, process analysis, operation analysis, motion study, time study, work sampling, and flow analysis are widely used. Similarly, among the charting techniques, process charts, pitch diagrams, multiple activity charts, process charts, and machine sequential charts are used. From among these various techniques, the appropriate one will be chosen, based on the object being analyzed. The details of the various techniques are explained in other chapters of this Handbook. In this chapter, we will briefly introduce the technique of time study using a VCR and the predetermined time study (PTS) method.

Time Study Using a VCR. In analyzing the current situation, it is essential to obtain the time value for each process and operation. To determine time values, conducting a time study using a stopwatch has been the main method for a long time (about 100 years). However, in order to obtain accurate measurements through time study by stopwatch, the time study analyst must have proper training. Certain preparations are also necessary, such as defining the elements to be measured, prior to actually making the observations.

There are several merits in using a VCR in time studies. For example, the problem of skill levels of the time study analyst is overcome, measurement accuracy is improved, elements can be accurately measured quickly, and a recorded image of the object measured can be kept. In the case of time study with a VCR, it is also not necessary for the operating procedures of the operator being measured to be fully stabilized. By using a VCR which records time values at the same time it records the image, the precision of establishing operation times can be greatly increased.

The PTS (Predetermined Time System) Method. When conducting a time study, no matter how accurately the time values of operations and elements are measured (for example, by using a VCR), the question of how to measure the operator's level of effort—in other words, the issue of performance rating—still remains. In fact, many problems that cannot be solved by an engineering approach remain. These include the problems of the skill level of the operators being measured, how to select a normal time from the various time values actually measured, and how to deal with the day-to-day variance in cycle time. To avoid problems like these, PTS methods can be used effectively.

First of all, with PTS methods, once the work methods are established, appropriate time values can readily be determined and the problems that occur in time study, such as performance rating, can be eliminated. In general, to become proficient in PTS methods, the use of quite a lengthy study time is required. However, new methods, primarily the MOST technique, have been developed that can be mastered quite quickly; therefore, the amount of training is no longer a barrier. Furthermore, when new methods are introduced based on PTS, then (a) the new method can be readily explained to anyone concerned and (b) following the implementation of the new method, the establishment of standard times becomes an easy task.

Step 4: Modeling the Area to Be Improved

In this step, the selected work system is modeled, based on the data gathered from the analysis of the current situation (Step 3), as the object of the improvement and design activities. This is done by selecting, for each parameter, the most typical value or status. The model is then defined in terms of the values or status descriptions of all relevant parameters.

The actual work system changes on a daily basis, due to a variety of factors. The work methods used by the operators, the condition of the machines, and the quality of the parts may vary

METHODS ENGINEERING AND WORKPLACE DESIGN

from day to day. In order to conduct improvement activities in an efficient manner, it is important to focus on the model of the work system as defined above, and not be distracted by the many factors impacting the system on a daily basis.

Creating an improvement plan is the action of defining the so-called one best way for the modeled system. Accordingly, no matter what current situation is selected as the standard at the start of the improvement activities, the ultimate solution will always be similar. To describe the model of the existing system, visual techniques such as layouts, drawings, process charts, and time charts are used, based on the analysis done in Step 3. (See Fig. 4.1.2.)

Step 5: Developing the Ideal Method

In creating the improvement plan, the steps for implementation vary somewhat according to the project—e.g., projects where the objective of the improvement activity is the very structure of a complex, multiprocess system versus projects where the objective is improvement of the work methods performed by the operators.

When the improvement involves changes to a multiprocess system, the first step must be to study the relationship between the various processes. In this step, the production system itself is examined and the approach will be selected after evaluating the suitability of line production methods, cell production methods, or individual production methods. Likewise, the relative merits of continuous flow versus cell production must be examined in this step. In case of line production, one must examine whether the situation calls for the production of a variety of product models on a few lines, or a limited number of models on multiple lines. Work in process, and the handling of materials within and between different processes, also can have a big impact on the production system. At this stage, possible changes to layout, material handling methods, and the production control system must be considered as well.

After completing the study of the relationship between the processes, one must next address improvements at the level of operations and motions. This activity will be most effective if it is focused on the lowest level (smallest elements) of work and if each factor is individually evaluated.

In studying the relationship between people and machines, it is necessary to address such issues as allocation of operators to machines and selection of optimum lot size, as well as the improvement of machine capabilities. On the other hand, in cases where the focus of improvement is on manual operations, the various industrial engineering improvement methods can be directly applied and project activities can start immediately.

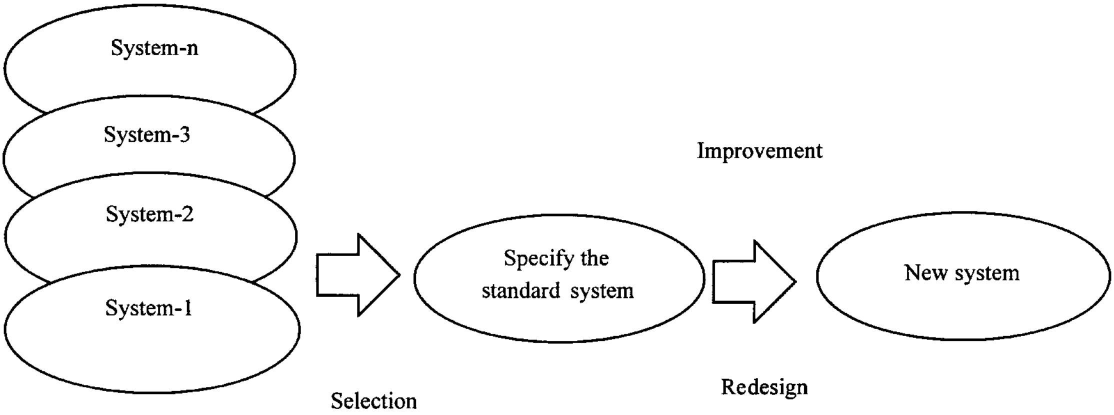

FIGURE 4.1.2 Specifying the existing system.

The following is an introduction to the tools that are effective in creating improvement plans, and the logic behind them.

Approaches to Analysis

- *Eliminate, Combine, Rearrange, Simplify (ECRS).* When thinking about how to improve a certain process or operation, an efficient way is to consider how to eliminate, combine, rearrange, and simplify (in that order) the components of the process or operation. If a function or action can be eliminated, the components or elements related to that function or action can be eliminated at the same time. For this reason, eliminate usually produces the best improvement results, and should therefore be the first activity considered.

Next consideration is how to combine. By finding opportunities to combine operations, tools, jigs, or parts and to perform simultaneous processing, we can often expect to reduce the amount of material handling as well. In addition, by rearranging, a better sequence for processes and operations may be formed, which frequently results in the elimination of repetitive or redundant work.

After these steps—eliminate, combine, and rearrange—have been completed, simplify will be considered. Simplify implies methods improvement, or *kaizen* in a narrow sense, and involves establishing in a very concrete and practical way the positioning of parts and materials, the layout of the work area, the use of appropriate jigs and tools, etc.

- *Principles of Motion Economy.* When considering ideas for improvements, applying traditional improvement principles is effective in that it reduces the chances of overlooking any potential improvement and enables the improvement activity to move ahead quickly. These principles have been organized into about 10 items in each of the following categories: (a) body movements, (b) positioning of jigs, tools, and materials, and (c) design of jigs and equipment. The Gilbreths, Ralph M. Barnes, Benjamin W. Niebel, Marvin E. Mundel, and others have introduced and described these principles. The content in most cases is quite similar, so the preferred version can be selected and the principles applied effectively. The study of principles of motion economy can, in fact, provide a very useful introduction to the whole field of work improvement.

- *Brainstorming.* In generating ideas for improvements, brainstorming can be a powerful method. This technique was developed by A. F. Osborne and is based on the formation of a brainstorming team consisting of several members who will be working to come up with improvement ideas and plans. If the team is made up of representatives from different areas of the company, ideas created from different perspectives will emerge and good results can be obtained. When putting forward ideas during brainstorming, some rules for maximizing the results include: do not criticize the ideas of others, it is acceptable to support the ideas of others, extreme ideas are permitted, try to generate as many ideas as possible, limit the brainstorming session to a set length of time, and keep a record of all ideas.

- *The 5W1H Method.* To accomplish the important step of verifying the necessity of existing work elements, the 5W1H method is effective. This method entails a clear definition of the conventional 4W1H (What? Where? Who? When? How?) in regard to the process or operation being studied, and in addition the question: Why? By repeatedly asking "Why?" one gradually recognizes the reason for being of some current practices. Although confirmed by conventional 4W1H, their existence may in fact be rather questionable. This way, the potential for making major changes often becomes apparent. In addition, the technique of seeking improvement ideas through the combination of the 5W1H method and ECRS can be quite useful.

The Design Approach. The methods and procedures for creating an improvement plan using a so-called analytical approach have been described above. This industrial engineering–style approach, which has been used for many years, clearly has some limitations: corrective action cannot be started until the problems are actually defined; the present conditions are so well known and accepted that they are not being challenged and no improvement ideas will come forward; attention is focused on various individual problems, and the thinking does not extend to the system in its entirety; and so forth. In consideration of problems like these, the method known as the design approach was developed. This style of thinking, originally advocated by Gerald Nadler and others, is essentially the application of product design methods to the improvement and design of work systems.

As shown in Fig. 4.1.3, the special features of this approach are the following: the first step is to clearly identify the functions of the work system targeted for design or improvement; second, without being bound by the current methods, an ideal system is designed; and third, system design is approached methodically, beginning with clear definitions of inputs and outputs. While it is true that a weakness of the design approach is that it takes time to create an improvement or design plan, a strong benefit is that in many cases substantial improvements can ultimately be made.

The Handling of Simulation Factors (As Part of the Evaluation of Improvement Plans). In creating an improvement plan, it is also necessary to clearly show concrete numerical values of a variety of evaluation parameters in the plan. The evaluation parameters selected may include labor productivity, equipment productivity, the volume of work in process (between processes), equipment utilization, and other measures such as throughput time. If the work system being evaluated is a small-scale system, it is relatively easy to evaluate the performance of the system. Evaluation can be done through the application of the analytical techniques mentioned above. However, for larger, more complex systems, evaluation of their functionality becomes more difficult. In such cases, utilization of computer simulation can be effective. For

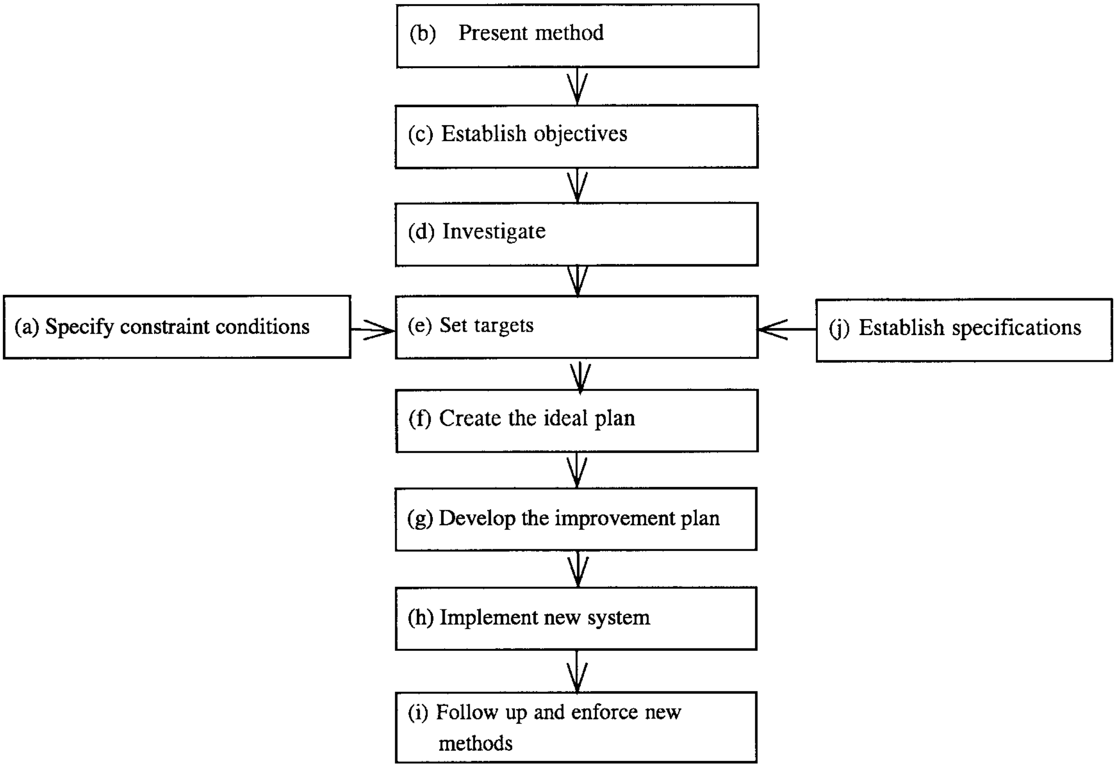
(b) Present method
(c) Establish objectives
(d) Investigate
(a) Specify constraint conditions
(e) Set targets
(j) Establish specifications
(f) Create the ideal plan
(g) Develop the improvement plan
(h) Implement new system
(i) Follow up and enforce new methods

FIGURE 4.1.3 Procedure for the design approach.

example, computer simulation is a particularly effective tool for such things as determining buffers for various line configurations, establishing the number of material handling vehicles or machines in a warehouse, or understanding the problem of robot interference in a manufacturing cell. Virtual factories are being put into operation and it can be expected that in the twenty-first century virtual reality will become a routine evaluation technique.

Alternative Plans. When creating an improvement plan, it is preferable to make several plans than to create just one. By creating several plans, each using different concepts, it becomes feasible to study the project from a broad viewpoint, and not many issues are likely to be overlooked. Eventually, the various plans will be evaluated according to uniform evaluation standards and the pros and cons of each will become clear. In this way, the best plan can be chosen with little chance of error. Also, at the stage that the various plan alternatives are being made, the preferences of team members with different opinions can be included. Involvement of all members, in turn, makes the eventual introduction and implementation of the plan go more smoothly.

Step 6: Selecting the Improvement Plan

In selecting the final plan from among several improvement plan alternatives, the best plan is chosen based on uniform evaluation standards for such things as cost of improvements, time required for improvements, and degree of technical difficulty. In cases where other improvement objectives such as expandability, flexibility, safety, operator comfort level, and matching the required skill level of the available operators have been included, obviously those parameters become part of the evaluation standards. Usually, different weights are assigned to each evaluation item, and in general the weight for each item is determined through averaging the inputs from a large number of participating individuals.

For parameters that can be evaluated quantitatively, as much as possible the quantitative yardstick should be set prior to the beginning of the evaluation. Even for parameters that can only be evaluated qualitatively, if at all possible a substitute parameter should be found so that a quantitative measure, albeit indirect, can be taken. (See Fig. 4.1.4.)

No.	Evaluation factor	Weight	Alternative Plan-1	Alternative Plan-2	Alternative Plan-3	Alternative Plan-4	Remarks
1	Productivity	15	E-4/60	G-3/45	E-4/60	G-3/45	
2	Quality	20	G-3/60	G-3/60	G-3/60	E-4/80	
3	Investment	5	F-2/10	P-1/5	G-3/15	P-1/5	
4	Safety	15	F-2/30	E-4/60	P-1/5	E-4/60	
5	Required skill level	10	G-3/30	G-3/30	G-3/30	E-4/60	
6	Time to implement	5	G-3/15	F-2/10	G-3/15	F-2/10	
7	Technical feasibility	5	G-3/15	F-2/10	E-4/20	F-2/10	
8	Ergonomics	15	G-3/45	E-4/60	F-2/30	E-4/60	
9	Ecology	10	G-3/30	E-4/60	F-2/20	E-4/60	
10							
	Total	100	295	320	265	350	

Note: Evaluation codes: Excellent = 4, Good = 3, Fair = 2, Poor = 1

FIGURE 4.1.4 Chart for evaluating alternative plans.

Step 7: Implementing Improved Methods

In implementing new methods, much preparation is required, including the detailed design, ordering, installation, and test running of equipment; education and training of operators; creation of user manuals; setting up maintenance procedures, and the like. In implementing small-scale improvements, the schedule can be monitored and managed through the use of tools like Gantt Charts. In more complex projects, where implementation activities are interrelated with one another, it is more beneficial to use methods such as project evaluation and review technique (PERT) and project management for managing the schedule.

Step 8: Follow-Up

After the introduction of a new system, it is essential to create a follow-up, or monitoring, procedure so that system performance can be maintained at the target level. Of primary importance for this are standard operating procedures for the new system and written standards and procedures for equipment maintenance. Moreover, it is essential to implement a measurement system so that it is always possible to verify that performance is being maintained at the expected level of the new design. In the case of improvements made within a factory environment, a measurement system utilizing standard times should be created and implemented.

METHODS ENGINEERING CASE STUDY

As indicated above, methods engineering is being applied in the improvement of a broad range of fields, from the processes and operations associated with manufacturing to the design and improvement of complex work systems composed of numerous activities. In this section, to aid in understanding the application of methods engineering, we will examine an example of a small-scale methods engineering project.

Step 1: Select the Study Subject. Outline of the study subject—i.e., the factory area targeted for improvement:

Scope: Factory manufacturing hard disks for computer memories (entire factory)

Number of Operators: Approximately 300

Process Steps: Incoming inspection, annealing, outer perimeter beveling, rough grinding, annealing, fine grinding, washing, inspection, packaging, shipment

Objective of Improvement Project: Increase production volume by 50 percent in the shortest possible time and with the least possible investment

Step 2: Establish the Objective and Project Specification. The objective of every improvement project varies according to the specific situation of each subject company. In some cases the objective may be the reduction of labor cost, while in others it is improvement of equipment productivity or yet a different goal. In the present actual case, the objective was to increase the total production volume of the whole factory. To increase a factory's production volume, the usual approaches include: expanding the factory, increasing the operating time of equipment, adding new equipment, increasing the number of operators, and so on. However, in this case, due to limitations both in available time and investment budget, it was necessary to focus on increasing production volume through improvement in productivity. Therefore, the objective and specification were established as follows:

Objective: Production volume of 100,000 disks/month (150 percent of the present volume)

Time to Reach Objective: 7 months

Number of Operators: Same as present

Investment Budget: The minimum required to achieve the above objective

Step 3: Do the Analysis. The goal of the analysis was to identify the production capacity of each process step and quantify the required amount of increase. In this factory, the production process consists of a linked series of fabrication steps, and significant variation in the apparent production capacity of each process step was a constant problem. Thus, it was necessary to establish the present situation of each process step in regard to actual capacity and to set an improvement goal for each step. To determine the production capacity of a process step, it was necessary to measure the number of equipment units, the number of operators, the cycle time for each fabrication step, the defect rate, and so forth. For establishing the cycle times, the usual practice is to make measurements using a stopwatch.

The actual situation for each process step and the increase (expressed as a factor) needed from the improvement activity are shown in Table 4.1.1 following.

From this analysis of production capacity by process step, an important fact can be seen. To increase the total factory production capacity to 150 percent of its present level, it is not necessary to increase the capacity of each production step by that amount. In fact, the capacity of only five production steps needs to be increased at all. Those steps are outer perimeter beveling, rough grinding, final polishing, and inspection.

Step 4: Modeling of the Area to Be Improved. From the analysis of production capacity by process step, it was determined that productivity improvement was needed only for five process steps. From among those we will here examine in detail only how the rough grinding step was improved. In order to establish a baseline, we must standardize the present situation. To do that, the present process is measured for one cycle and a model is established. Even though, in practice, there may be variations in how work is actually done (according to shift, individual operator, etc.), it is this static model that is analyzed for improvement. In this particular case, stopwatches were used to measure each operation, and a multiactivity chart was created. The results are shown in Fig. 4.1.5 (Chart #1).

Step 5: Develop the Ideal Method. After defining the model of a certain area, improvement ideas are developed through brainstorming and other methods. Many ideas were put forth for the improvement of rough grinding, and those that involved methods improvements were as follows:

- To reduce loading and unloading times of the aluminum substrates that will be processed into hard disk memory media:
  1. Have two operators perform substrate loading/unloading, making use of idle time
  2. Make a jig to aid in substrate loading/unloading
  3. Do setup operations off-line
- To reduce grinding time:
  4. Increase grinding pressure
  5. Use thinner blank materials
  6. Use a coolant with better efficiency
  7. Increase grinding speed
- To reduce or eliminate waiting for measurement time:
  8. Increase the number of calipers available for use in measuring
- To reduce dressing time:
  9. Redesign the dressing tool

Step 6: Selection of Best Improvement Ideas. The ideas brought forth in the previous step are selected for adoption or rejection considering productivity improvement, quality, amount

TABLE 4.1.1 Determining the Production Capacity of Each Process Step

		Equipment units	Process lot size	Cycle time (min)	Operating time (min)	Utilization factor	Non-defective factor	Production capacity (disks/day)	Necessary increase (factor)
1	Incoming inspection	8	1	0.03	480	0.95	0.98	119168	0.84
2	Annealing	1	25000	300	1440	0.99	0.95	112860	0.89
3	Outer perimeter beveling	16	1	0.3	1440	0.9	0.99	68429	1.46
4	Rough grinding	16	12	3.9	1440	0.98	0.97	67390	1.48
5	Annealing	1	25000	300	1440	0.98	0.98	115248	0.87
6	Finish polishing	16	12	3.5	1440	0.9	0.95	67540	1.48
7	Wash	6	1	0.1	1440	0.95	0.9	73872	1.35
8	Inspection	4	1	0.05	1440	0.8	0.88	81101	1.23
9	Packaging	4	1	0.03	1440	0.9	0.99	171072	0.58
10	Shipping	1	6000	20	480	0.9	1	129600	0.77

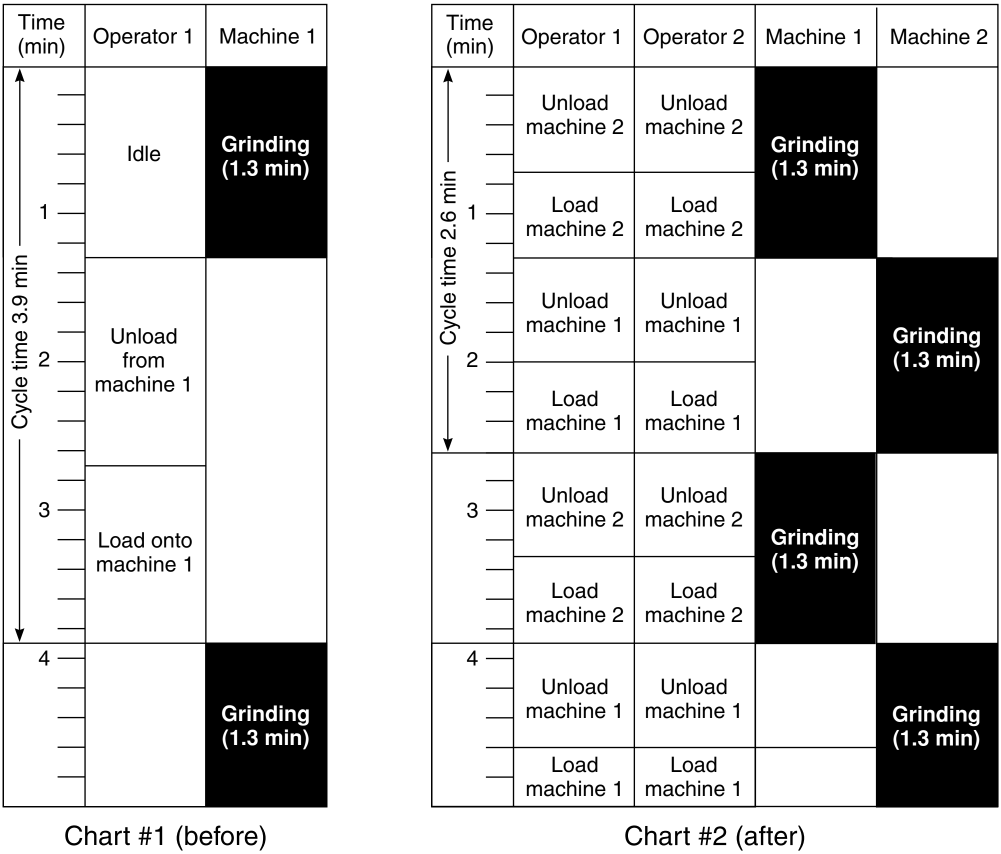

FIGURE 4.1.5 Multiactivity charts.

of required investment, safety, and so on. In this actual case, each idea was evaluated according to the following evaluation table (see Table 4.1.2) and in this case, ideas 1, 8, and 9, which had high scores, were selected for implementation.

Step 7: Implement Improved Methods. In this step, the objective is to install any new equipment required and have all operators fully master the new methods. In order to achieve the target schedule, the various tasks needed to implement each improvement are broken out and scheduled. (See Table 4.1.3.)

Step 8: Follow-up Techniques. In some cases, even after successful adoption, new methods gradually break down. In order to avoid this kind of problem, constant monitoring of the factory floor and implementation of measuring systems are essential. In the present case, not only were improved systems implemented to increase productivity at each process step, but procedures were also put in place to enable prompt identification of problems and a quick response to those problems.

By compounding methods improvements of the type described above, the cycle time for rough grinding was reduced to 2.5 minutes, as shown in Fig. 4.1.5 (Chart #2), which is better than the target cycle time of 2.64 minutes.

TABLE 4.1.2 Evaluation Chart for Submitted Ideas

No.	Evaluation criteria	Weight	Idea 1	Idea 2	Idea 3	Idea 4	Idea 5	Idea 6	Idea 7	Idea 8	Idea 9
1	Productivity	30	E-4/120	G-3/90	G-3/90	F-2/60	F-2/60	G-3/90	F-2/60	F-2/60	F-2/60
2	Quality	10	E-4/40	F-2/20	F-2/20	P-1/10	P-1/10	G-3/30	P-1/10	E-4/40	E-4/40
3	Investment amount	10	E-4/40	G-3/30	F-2/20	E-4/40	F-2/20	P-1/10	F-4/40	G-3/30	G-3/30
4	Safety	5	E-4/20	E-4/20	F-2/10	E-4/20	E-4/20	E-4/20	E-4/20	E-4/20	E-4/20
5	Required skill level	10	F-2/20	F-2/20	F-2/20	E-4/40	E-4/40	E-4/40	E-4/40	E-4/40	E-4/40
6	Time to implement	10	E-4/40	G-3/30	F-2/20	E-4/40	F-2/20	F-2/20	E-4/40	E-4/40	G-3/30
7	Technical feasibility	15	E-4/60	P-1/15	P-1/15	P-1/15	P-1/15	P-1/15	P-1/15	E-4/60	E-4/60
8	Ergonomics	5	G-3/15	G-4/20	F-2/10	E-4/20	E-4/20	E-4/20	E-4/20	E-4/20	E-4/20
9	Ecology	5	E-4/20	G-4/20	G-4/20	E-4/20	E-4/20	E-4/20	E-4/20	E-4/20	E-4/20
	Total score	100	375	265	225	265	225	265	265	330	320

Note: Evaluation codes: Excellent = 4, Good = 3, Fair = 2, Poor = 1

CURRENT STATUS OF METHODS ENGINEERING

As indicated above, methods engineering has occupied the position as a key industrial engineering discipline for almost one hundred years. This staying power is proof enough as we begin the twenty-first century that this technique has not lost its importance. In fact, when a factory's production engineering staff and technicians tackle problems of system improvement, methods engineering is still the core technology they use. Moreover, this technology is important not only to industrial and manufacturing engineers and others involved in production technology; it is also recognized as essential knowledge for engineers in other fields, including product design and electrical, mechanical, and chemical engineering. Furthermore, its importance is not limited only to so-called professionals such as engineers and technicians; it can also lead to excellent results when used as the key tool in the hands of employees in general, as they conduct so-called *kaizen* activities or small group activities.

Finally, methods engineering was originally applied when the target for improvement was factory shop-floor, but recently its scope of application has been increased to include indirect work, office work, service work, and the like, indicating that today its effectiveness and importance have by no means diminished.

METHODS ENGINEERING IN THE FUTURE

Present day work systems may not be perfect. In newly built work systems, many imperfect points remain, and there will be room for further enhancement through improvement activities. The function of methods engineering is then to be employed continuously to raise these imperfect work systems ever closer to perfect systems (or as Toyota expresses it: "The relentless pursuit of perfection"). The need for methods engineering is likely to increase in the future.

Modern work systems are already at a high level. The elements that make up these systems are numerous, and the elements themselves are becoming more complex through the continuous increase in automation, precision, and specialization. Nevertheless, these high-level sys-

TABLE 4.1.3 Implementation Schedule

No.	Improvement	Actions	Responsible person	Week # W1	W2	W3	W4	W5	W6	W7	W8
1	Two operators to load/unload	Create written operating procedure	A	*							
		Select operators for model line	B		*						
		Implement on model line	B			*					
		List problems	A, B			*					
		Solve problems	A, B				*				
		Roll out to all operators/lines	C					*	*	*	
		Complete									*
2	Increase number of calipers	Select calipers	D	*							
		Order calipers	D	*							
		Design caliper stand	E	*							
		Order caliper stand	E		*						
		Complete caliper stand	E				*				
		Determine location for stand	E			*					
		Install stand and calipers	D, E					*			
		Complete	D					*			
3	New dressing tool	Design new tool	F	*	*						
		Order new tool (one)	F			*					
		Install new tools (part one)	F					*			
		List up new tool problems	F					*			
		Solve new tool problems	F						*		
		Order 10 new tools	F						*		
		Install new tools (part two)	F								*
		Complete									*

tems must be further improved and redesigned, and an important challenge today is how to apply methods engineering to these ever more complicated, ever larger systems in the future.

Concerning the element that make up systems, perhaps the major contemporary characteristic is the rapidly growing importance of information-related elements. Looking at manufacturing systems, the interaction of people and machines can be expected to continue to be significant, and it must also be recognized that the quality of materials will have an increasing impact on their efficiency. As the factors relating to systems become increasingly numerous and complex, the pathways to achieving system improvement, or even to identifying goals and problems, become multibranched and complicated. In such an environment, inevitably there will exist many possible approaches to system improvement.

As indicated above, the systems themselves that become the objects for improvement activities are no longer just manufacturing systems—any work systems that exist today may be addressed. In addition, the objective of a methods engineering activity is no longer limited to the reduction of total cost, but may extend to such goals as improvements of an ergonomic character, balance between the production system and the environment, and customer satisfaction.

In a climate of changes to systems themselves, to the elements that make up the systems, and to the objectives of improvement activities, the demands being placed on methods engineering are becoming more extensive. With such changes occurring in both internal and external environments, strong expectations will be placed on the traditional industrial engineering techniques of performing analysis, modeling, design, and establishment of standards used in methods engineering. With more and more people having to deal with improving the new, gigantic, and complex systems, new methods for analysis and problem solving are already being born. We can expect these new techniques to play a key role in the development of the next generation of methods engineering.

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BIOGRAPHIES

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Source: MAYNARD'S INDUSTRIAL ENGINEERING HANDBOOK

CHAPTER 4.2

CONTINUOUS IMPROVEMENT (*KAIZEN*)

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Although employees have unlimited opportunities to improve workplaces, most companies tend to believe that "further improvement is impossible." However, substantial improvement of workplaces is always possible if the perspectives and concepts regarding work are changed.

When considering the approach of continuous improvement, workplaces can be divided into two types. Type A workplaces are essentially people (labor) intensive and include assembly lines and logistic operations, while Type B workplaces such as processing or fabricating facilities are machinery and facility intensive. In either case, appropriate improvement objectives might include productivity improvement, expansion of production capacity, or adaptation of production for multiple products in small lots. Based on each of these objectives, this chapter demonstrates examples of hidden losses (waste) and provides a collection of checkpoints for improvement (improvement rules) within the concept of continuous improvement or *kaizen* in Japanese.

*TECHNIQUES FOR ACTIVATING A CONTINUOUS IMPROVEMENT (*KAIZEN*) PROGRAM*

Kaizen, or *continuous improvement,* is defined as follows: "Based on a request from top management or a downstream manufacturing group, set up an improvement activity with participation of all employees and perpetually expand this program."

Therefore, in this chapter, as a background to the actual procedure of continuous improvement, the reason why improvement is needed more than ever and the importance of autonomous improvement by all members are explained.

Continuous improvement, however, is not always applied successfully in all companies. For this reason, a brief description of common problems in workplaces where continuous improvement programs have not been successful is provided. Two counteractions to eliminate such problems—how to develop an *improvement mind* and programs for conducting *improvement campaigns*—are also introduced.

To conclude the chapter, an effect index and key points for success in relation to continuous improvement programs are presented.

The Need for Continuous Improvement

Improvements must not be tried as a spot activity only for a certain period of time. In view of the following background, improvement activities must be established in the workplace with the participation of all members and be expanded and further developed over time.

- Improvement ideas exist without limit, given the transforming environment inside and outside the company. An example of an external factor is the necessity for a review of product designs and production processes in response to environmental problems and to the needs for resource conservation and energy savings. Moreover, higher quality, up-to-date products, faster delivery, and lower prices are demanded by the customers.
- The most successful implementation of improvements occurs when the fundamental policies of top management are accurately conveyed to all organizational levels of the company. In many companies, basic policies like “This year we want to be like this!” are introduced by top management. However, not all companies are successful in getting those policies implemented accurately and concretely in all departments and workplaces. In some firms, the fact is that improvement activities are not progressing. To realize the kind of high-level production facility that top management desires, a wide-ranging, long-lasting, and steady improvement program is required.
- Between an ideal situation and what is actually accomplished, there is often a big gap. Almost all workplaces have shown considerable improvement compared to the past. However, even though all employees may be thinking “We want to make our workplace like this!” (their ideal image), there still remains a gap between that image and their present situation and current accomplishments. The company’s ideal image of its factory may include such goals as to produce x units per labor hour, to increase production volume by 50 percent with the present fabricating machines, to reduce defects and rework to zero, to handle small lot production of a variety of products without generating excess inventory or encountering shortages, to make a big reduction in manufacturing lead times, or to create a production system which can be used anywhere by anybody. However, the higher the level of the ideal image, the bigger the gap between it and reality. Usually, these ideal images are established by a reverse calculation which indicates that the company cannot be maintained (survive) unless these higher levels are achieved. Therefore, we must continually pursue *kaizen* activities to eliminate this gap. Even in companies where employees believe “There is no more room for improvement!,” in reality various hidden losses still exist in most cases, when compared to production facilities which have continually pursued attainment of their ideal images.

The above should clarify the reason and background of the motto, “improvement activities must be never ending.”

THE IMPORTANCE OF AUTONOMOUS IMPROVEMENT

The completion of a major production reengineering program, including improvements to materials and product designs and the introduction of innovative new equipment with heavy investment, is often pursued using a core team of experts and specialists. However, in addition to such major projects, every production facility holds many near-at-hand opportunities for improvement. The company’s management and staff, however, often overlook these. Some examples of opportunities for improvement, which could be done by production line members themselves taking the lead, include reduction of time and alleviation of fatigue through work simplification, increasing the equipment utilization rate, reduction of set-up and changeover times, raising line organization efficiency, and saving space.

In order to conduct continuous improvement activities at the workplace in a sound and reliable fashion, the most essential factor is a sense of involvement on the part of all the members involved. In most cases, line operators on the factory floor will not readily accept a plan prepared solely by management and supervisory staff. In general, plans conceived and proposed by the members who work on the factory floor have significantly higher rates of successful implementation. In fact, most operators feel "I want to contribute as much as I can to the group I belong to!," or "I want to be recognized as a worthy member of the group!," or even "I want to make this workplace better!" Nobody thinks "I want to make my workplace bad!" because they are aware that if the productivity of their workplace declines, it will negatively impact them in terms of pay and benefits.

Continuous autonomous improvements by production line members can accumulate into major savings and enhancements.

POTENTIAL PROBLEMS WITH CONTINUOUS IMPROVEMENT

When different companies are compared, there is a big variation in their autonomous continuous improvement activities conducted by line members, in regard to both the extent and the effect. Looking at companies where those activities are rapidly progressing compared to the ones which are slow-moving, we can see a variety of differences. Those differences can be classified according to the following ten factors. In other words, these are the problems, which must be overcome to run an active and successful continuous improvement program.

1. The attitude that "Our work is being done just fine" or "Compared to the past, our work has been greatly improved" leads to the belief that "There is no more room for improvement!" Furthermore, even if the members were to accept the need for further improvement to their workplace, they would not know how to proceed.

2. A lack of improvement ideas. No one comes up with ideas for improving the situation. Even if there is a consciousness of the need to look for waste in the workplace, no one translates that into actual improvement ideas. In particular, the bud of an idea like "This could be changed in this way" is usually nipped by the members themselves, since they immediately start to think of the constraints and assumptions that exist in the present situation. Moreover, even if a member comes up with an idea, he or she may be afraid that others will say "That will not work because . . ."; therefore, no one will make his or her ideas known.

3. Difficulty on the part of the participants in explaining the essentials of their improvement ideas. If the content and effect of an improvement idea cannot be effectively explained, even a good idea will not be properly conveyed. The presenter may be told to put the idea in the form of a written improvement proposal, but he or she may not have the skill to do that.

4. Preoccupation with daily work, leaving participants no time to think about improvements. Being busy all day in the workplace dealing with routine work, participants have little time to think about improvement proposals. Besides, there is no time to write a proposal document or discuss it in a group.

5. Lack of pressure to come up with improvements, so no one presents opinions about improvements. Even if someone has a suggestion for an improvement, neither superiors nor colleagues will routinely ask "What is your opinion?"; therefore, ideas never get expressed. Many operators would offer an opinion if asked, but they do not have the courage to speak out on their own initiative.

6. Failure of the company to create an atmosphere where improvement proposals are welcomed. Even if someone makes an improvement proposal, he or she is seldom praised for it.

Rewards or commendations for good ideas are rarely given. In contrast, the employee may be scolded: "Why have you been doing it that way (the old way) all this time?"

7. Slowness in evaluating proposals and reporting management decisions about adopting them. After submitting a proposal, it takes a long time to get any feedback.

8. Lack of management interest in improvement proposals or in revising, promoting, or extending them. Superiors and office staff just classify the improvement proposal or improvement idea as *adopt* or *do not adopt.* However, some of the rejected ideas, through revision of content or combination with other ideas, could be changed to *adopt* and big benefits could be uncovered in the process.

9. Slowness in implementing ideas or plans. The preparations for implementation may be troublesome, making the idea work with other process steps may be difficult, and gaining acceptance by other members may take time. For these reasons, the enthusiasm of the proposing member gradually diminishes.

10. Poor follow-up after implementation—no one bothers to evaluate or measure the impact of the idea. In some cases, there is no clear benchmark for measuring the effect after the introduction of an improvement idea. Even if a benchmark is established, it may not be used effectively to recognize the impact of the idea, so that the proposing members will never enjoy the satisfaction and feeling of achievement reflected in "We did it!"

The above ten problems are the major obstacles to effective continuous improvement programs.

MEASURES FOR EFFECTIVE APPLICATION OF CONTINUOUS IMPROVEMENT

Through various efforts, companies have solved the previously mentioned ten problems and are enjoying steady results and benefits over the long term. In general, the scope of the counteractions to solve these problems can be roughly classified in two categories as shown in Fig. 4.2.1.

Involving All Members and Activating and Perfecting in Their Minds an "Improvement Consciousness"

Among the ten problems mentioned above, (1), (2), and (3) in particular can be solved by finding a way to instill in the minds of all employees the attitude: "Let us make our workplace as good as we can!" To accomplish that, the members must first thoroughly understand the necessity for improvement. To be specific, top management and superiors in the workplace need to explain to all the members repeatedly not only the present business situation and the competitive environment the company faces, but also the vision the company is targeting. Then, as often as possible, review meetings should be held in which the improvement program for each workplace is explained and actual improvement examples are described in an easy-to-understand way.

The following are concrete examples of effective measures for accomplishing the above:

- Holding periodic (e.g., two hours every month) improvement training meetings for all the members.
- Holding meetings in which core members of the team conduct practical exercises in how to make improvements.
- Implementing *self-checkups* in every workplace.

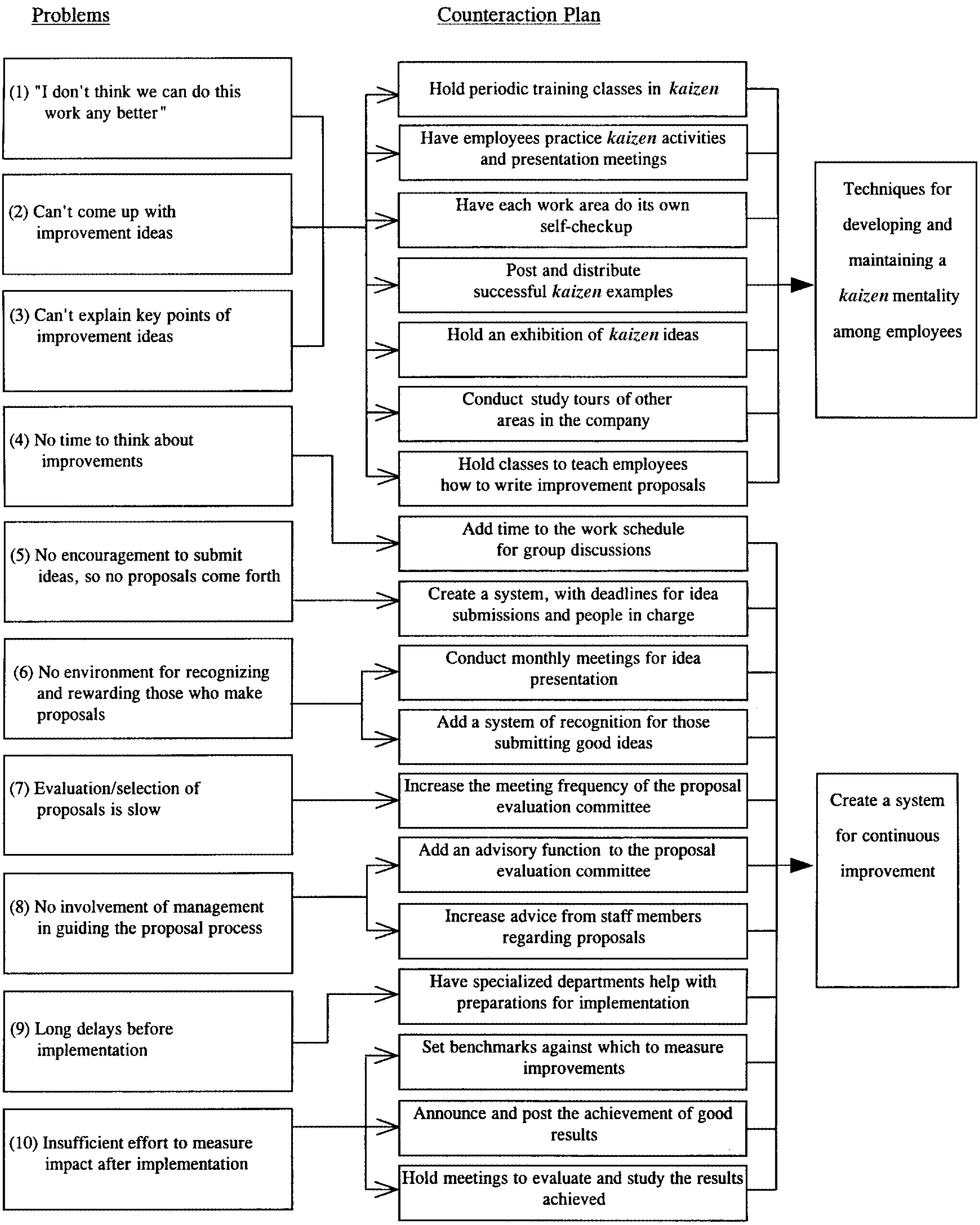
Problems
Counteraction Plan
(1) "I don't think we can do this work any better"
(2) Can't come up with improvement ideas
(3) Can't explain key points of improvement ideas
(4) No time to think about improvements
(5) No encouragement to submit ideas, so no proposals come forth
(6) No environment for recognizing and rewarding those who make proposals
(7) Evaluation/selection of proposals is slow
(8) No involvement of management in guiding the proposal process
(9) Long delays before implementation
(10) Insufficient effort to measure impact after implementation
Hold periodic training classes in *kaizen*
Have employees practice *kaizen* activities and presentation meetings
Have each work area do its own self-checkup
Post and distribute successful *kaizen* examples
Hold an exhibition of *kaizen* ideas
Conduct study tours of other areas in the company
Hold classes to teach employees how to write improvement proposals
Add time to the work schedule for group discussions
Create a system, with deadlines for idea submissions and people in charge
Conduct monthly meetings for idea presentation
Add a system of recognition for those submitting good ideas
Increase the meeting frequency of the proposal evaluation committee
Add an advisory function to the proposal evaluation committee
Increase advice from staff members regarding proposals
Have specialized departments help with preparations for implementation
Set benchmarks against which to measure improvements
Announce and post the achievement of good results
Hold meetings to evaluate and study the results achieved
Techniques for developing and maintaining a *kaizen* mentality among employees
Create a system for continuous improvement

FIGURE 4.2.1 Problems with continuous improvement programs and suggested counteractions.

- Posting lists of improvement hints (collections of examples of actual improvements) and distributing this information to all members in the form of handouts.
- Holding improvement exhibitions, i.e., displaying actual improvement examples, including photographs, videos, or improved items in the factory lunchroom or in other suitable locations. Sometimes it may be useful also to show examples of unsuccessful attempts.
- Implementing a program of study visits to other workplaces in the company (or a "student exchange" type program, between different areas within the company).
- Holding classes in proposal writing.

Through such indoctrination approaches, an *improvement mind* can be instilled in employees and their skill levels in regard to making improvements can be raised.

Creating Systems and Techniques for Dramatically Strengthening Improvement Activities Within an "Improvement Campaign" Program. In order to solve the above-mentioned problems (4) through (10), systems must be created which will fully release the potential capabilities of the members. The following are examples of such systems, which have been effective in practice:

- Include time in each month's work schedule for group discussions. Every month, at a time when the workload is relatively light (such as the beginning or middle of the month), systematically set aside time for a discussion. One way to do this is to assign a group of members to improve the efficiency of the daily morning meeting or the end-of-the-shift cleanup activities, and use the time gained for a monthly group discussion.
- Implement an Idea Submission Day scheme and appoint a person to gather the ideas. For example, designate every Friday as Idea Submission Day and send one employee around to solicit improvement ideas from the other members of the group. This particularly helps reticent members who will give an opinion only when "called upon." The task of soliciting ideas can be given to a member of the Improvement Promotion Committee for the particular workplace.
- Hold Improvement Presentation Meetings each month in each division of the company, attended by top management, other managers, and a representative of each group. Not all the members can attend each meeting, but key people may be able to attend by taking turns. These meetings will enable members from one group to learn about the progress of the improvement activities of other groups, and use that information to further improve their own activities.
- Change the role of the proposal evaluation committee. Some of the improvement proposals which were ruled *do not adopt,* could be changed to *adopt* (and also receive a commendation) by revising their contents. Therefore, the advisory function of the review committee should be expanded to evaluate the contents of those proposals classified as *do not adopt* and make suggestions such as "Try changing your proposal in this way; it might then be usable." This advisory function can become even more important by completing tasks other than the simple commendation ranking of the adopted proposals.
- Announce the impact of adopted proposals. Starting with benchmarks for each workplace, the daily, weekly, and monthly productivity indices should be displayed for everybody to see. The actual effect of the various improvement actions can thus be clearly shown in terms of improved productivity. By displaying improvement results in a form that everyone can see, the members can take pride in saying "I contributed to this improvement!," which should lead to an eagerness to aim at even higher improvement levels.

In order to motivate all employees to pursue major improvements, a well-prepared *improvement campaign* program, including the above-mentioned elements, can be effective. Such an improvement campaign program can function as a basis for achieving continuous improvement and also as a basis for motivating all employees to promote improvement activities.

EXAMPLES OF SUCCESSFUL IMPROVEMENT CAMPAIGNS

At many companies, improvement campaigns have been adopted as a tool for generating, maintaining, and expanding improvement activities. However, the specific content and conduct of the campaign vary according to the circumstances in, and background of, each company. Therefore, from numerous campaigns, two typical examples will be described here.

Example 1: Self-Checkup Strategy

Many adults get health checkups regularly, which are useful for the early discovery of illnesses, the symptoms of which are as yet unnoticed. In the same way, work at a factory can be thought of as a body needing periodic checkups. In a factory or other workplace, even though one believes that "The situation is fine," the routine checking of predetermined parameters every six months can be an effective *self-checkup.* From the results of this examination, hidden issues can be found and the potential for further improvement can be confirmed. For example in an assembly line situation, the items to be examined are shown in Table 4.2.1.

TABLE 4.2.1 Example of Self-Checkup Factors for an Assembly Line

Self-checkup factor	Measure	Result	Target value
Line stoppage rate	Total stoppage time/working time	12%	0%
Line balance ratio	Total time per station/takt time × number of stations	75%	90%
Percent of working time for non-value-adding functions	Time for functions like picking up parts or tools, making corrections or adjustments, divided by total working labor time (measured by work sampling)	40%	20%

Checkup items of this type can be analyzed by employees autonomously.

In general, no one feels good to hear "Look how bad your workplace is!" even if he or she is aware of it. However, if the group analyzes its own situation as a team and confirms the results, resistance is greatly reduced. As a result, a positive attitude is created in the members and they seek to begin improving the problem areas, which they have confirmed.

The steps of this self-checkup procedure, based on a case of self-analysis using video recordings, are shown in Fig. 4.2.2.

Example 2: Vision Strategy

In every workplace, there are aspirations like "In the future, we would want our workplace more like this!" or "We want to raise our workplace to this level!" Such goals become the company vision. Typical examples of vision goals are:

- Improve a poor work environment with bad smells, intense heat, low temperatures, untidy conditions, and the like, or shorten the working time (exposure) in such a workplace as much as possible.
- Cross-train employees to work in any workplace.

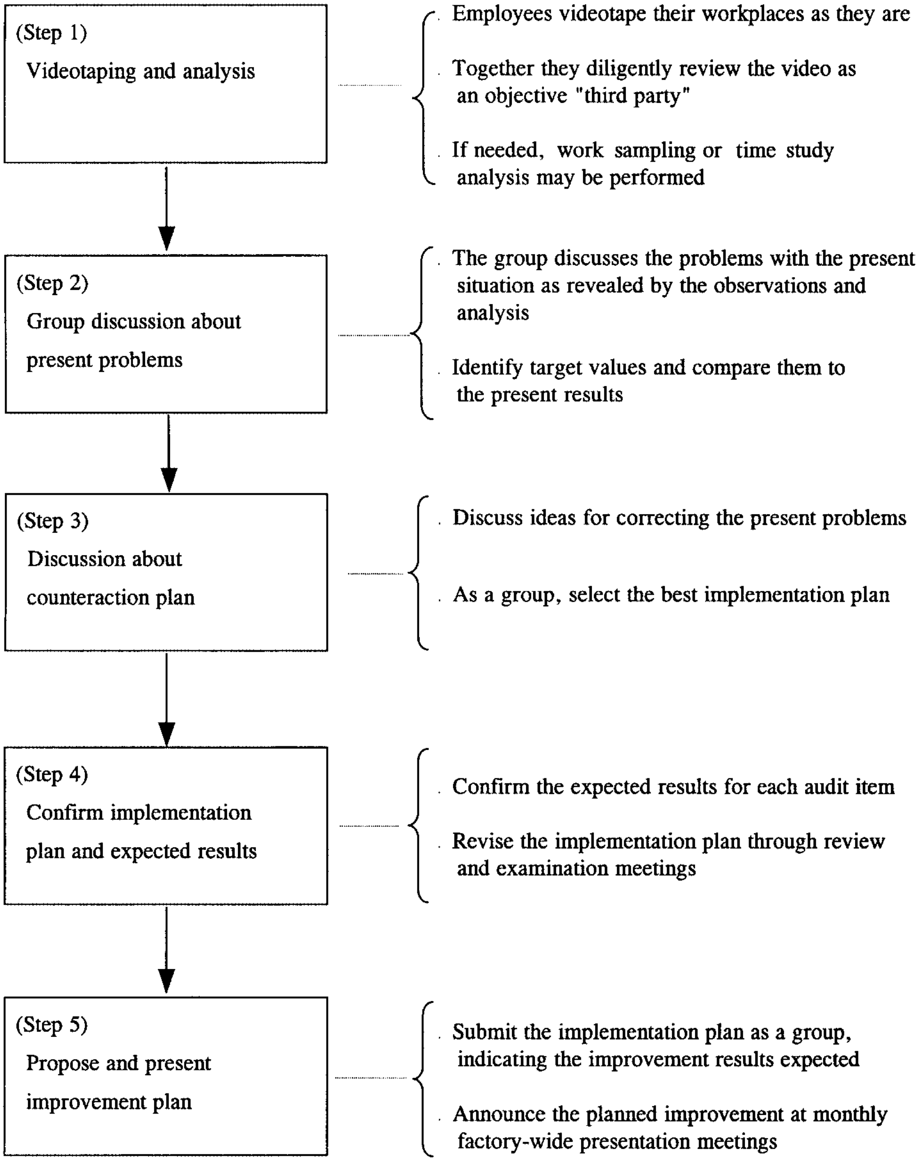
(Step 1)
Videotaping and analysis
Employees videotape their workplaces as they are
Together they diligently review the video as an objective "third party"
If needed, work sampling or time study analysis may be performed
(Step 2)
Group discussion about present problems
The group discusses the problems with the present situation as revealed by the observations and analysis
Identify target values and compare them to the present results
(Step 3)
Discussion about counteraction plan
Discuss ideas for correcting the present problems
As a group, select the best implementation plan
(Step 4)
Confirm implementation plan and expected results
Confirm the expected results for each audit item
Revise the implementation plan through review and examination meetings
(Step 5)
Propose and present improvement plan
Submit the implementation plan as a group, indicating the improvement results expected
Announce the planned improvement at monthly factory-wide presentation meetings

FIGURE 4.2.2 Conducting a self-checkup using video.

- Increase the production volume without increasing the production time.
- Maintain the present production volume with reduced labor resources.
- Apply "quick change" when product changeovers occur on the line.
- Drastically reduce inventory and work-in-process between process steps.
- Attain a high quality level and maintain it as standard.

The *vision strategy,* based on the policies set by the company, first establishes the desired profile in terms of the factors listed above. Thereafter, this strategy calls for alternative scenarios on how to move from the present situation to the future conditions envisioned by the members as a group by increasing levels of improvement. The steps for such a program are shown in Fig. 4.2.3.

The key features of the vision strategy are as follows:

- Since all the members of the business unit participate in establishing the vision, selecting the strategy and direction for improvements will be done thoroughly.
- In establishing the vision, existing constraints should not be considered, in order to make the climate right for innovative ideas to come forward.
- Once the vision has been established, the focus will turn immediately to planning. Because of their involvement, members will likely feel that "Something like this we can certainly accomplish!" and their level of enthusiasm for improvement activities will rise dramatically.

An improvement campaign should not be repeated year after year based on the same program, because, as is well known, people soon tire of doing the same task repeatedly. Companies which have pursued continuous improvement activities for a long time find it advantageous to add variety to the programs and typically introduce a new campaign about every three years.

AN EFFECT INDEX FOR CONTINUOUS IMPROVEMENT

The *effect index* used in a company which has been conducting continuous improvement activities will be determined by:

- The number of improvement proposals from the members. Quantitatively this is shown by the total number of proposals received from all employees and the average number of proposals per employee per year. Based on experience with using the effect index, companies have found a strong positive correlation between the number of proposals submitted and the number of improvement projects accomplished as well as the amount of reduced cost. The average number of proposals per employee per year in companies conducting improvement campaigns is about 20 . . . and higher for the most efficient companies.
- Labor productivity. Most factories express labor productivity in terms of annual (or monthly) production revenue (volume) per employee, determined by dividing production revenue (volume) by total number of direct employees. Alternatively, the amount of annual cost reduction may be used, in which case primarily labor costs are considered.

In addition, depending on the improvement policy of the individual company, the following may be included in calculating the index:

- Actual utilization rate of key equipment
- Production lead time
- Product defect rate

Check Points for Succeeding in Continuous Improvement

To keep continuous improvement activities moving ahead consistently, the participation of all associates is necessary. Then, for the campaign to be successful, the following points are essential:

Steps	The Case of an Inspection and Packaging Process
(Step 1) Vision formulation by workplace	* Due to a shortage of personnel, reach the present production level with two employees instead of the present eight * Reduce to one the number of times a product is handled * Reduce operator fatigue
(Step 2) Create scenario to transition from the present state to the vision	Three levels of "scenarios": * Present situation inspection and packaging requires eight employees * Initial improvement plan through integration of the inspection and packaging processes, work simplification, and "standardization of work methods reduces the staffing level from eight to four * Vision through investment in equipment to achieve automatic loading and unloading of products makes a further reduction from four operators to two
(Step 3) Concrete planning of initial improvement plan	Example of a detailed plan for implementing the initial improvement plan: * Introduce a new inspection method whereby the product is inspected on a cart, without being picked up * Integrate the inspection and packaging functions * Standardize the design of packaging * Reduce staffing of the large product packaging function from two operators to one
(Step 4) Confirm the results of the initial improvement plan and begin preparation of a revised plan	* Quantify the effect of the improvements for each product class (small, medium, and large) * Review the work method for large products (revise the present plan)

FIGURE 4.2.3 Pursuing the vision strategy.

1. Explain the goals of the improvement activities, their purpose, and their direction. The basic corporate policy must be broken down into activities and objectives for each group in the company, and this total strategy must be thoroughly understood by all the employees. For example, the objectives may include to develop systems to increase production by 30 percent, to increase production volume per associate by 50 percent, to reduce the production lead time at this workplace to two days, or to reduce changeover time to 20 percent of present time. These objectives must be conveyed to all employees in words that they can readily understand. To be successful, the improvement strategy must point the faces of all employees in the same direction.

2. Schedule limited time periods for specific activities. It can be very effective to set fixed time periods for campaigns which focus the knowledge and strength of the members on a certain topic. For example, Proposal Promotion Month, Safety Week, or a production strengthening campaign for a set period can produce good results. Well-planned campaigns involving the entire company can be a stimulating shot in the arm to activate workplaces where employees have only been paying lip service to improvement activities or performing them without enthusiasm.

3. Define individual steps. Even if employees have an improvement mind, there may be cases where individuals do not understand their specific roles. Besides, they may struggle as a group, wondering "What is the best way to proceed?" For this reason, the specific steps of each campaign should be clarified.

4. Create team spirit through a sense of "We're doing this together." Existing group activities, presentation meetings, proposal "exhibitions," and in-company *kaizen* study sessions will stimulate others to think: "Look at how active that group is. Let us not get left behind." This effort results in a synergistic effect and can launch an extraordinary improvement explosion throughout the company.

5. Establish a system that clearly recognizes people and announces the results of their efforts. If the benchmarks for improvement results are clear, and actual results show improvements, this increases the confidence of the participants and starts a positive cycle, encouraging members to target the next level. If the results of group activities are fairly evaluated and recognition given in an appropriate and timely way, enthusiasm for improvement activities will surely expand throughout the company.

By fully implementing the above key points, solid results can be achieved, and the resulting pride and satisfaction will spread to all employees. This in turn becomes a major activator, stimulating employees to move on to the next improvement activities.

CONCLUSION

A systematic *kaizen* program can contribute to increased corporate profits through increased quality which surpasses that of competitors, wide-reaching cost reduction, and dramatic reduction in delivery time. In today's competitive environment, it is more important than ever that all employees of manufacturing companies not only perform conscientiously the work they have been given but also actively participate in *kaizen* activities.

Kaizen activities not only contribute to improved profitability, which is the source of corporate growth, they often enable companies to unveil potential strengths and capabilities they had not recognized before. Such activities may further corporate development in other ways. For example, by promoting a sense of cooperation and shared goals among related departments, unified action to deal with problems may be achieved throughout a production facility, even including the indirect departments.

In general, most companies tend to believe that "There is no way we can improve further! . . . We have no more areas to apply *kaizen.*" However, if enough employees can change their attitude toward their work, they can stimulate the group to tackle many more areas for potential improvement. For example, most companies which have succeeded in changing their way of thinking can look back and remember that three or four years ago they too felt that there was no room for further improvement. Yet, with a new, positive attitude they went on to make significant additional improvements. This situation frequently occurs and proves that *kaizen* has no limits.

It is also true that "The more outstanding the company is, the more aggressively they pursue *kaizen.*" As a result, in the future, the gap between the outstanding companies and those satisfied with the status quo will continue to widen.

In the future, also, it will remain true that "For every employee, *kaizen* ideas are unlimited."

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BIOGRAPHY

Yoshinori Hirai is a senior consultant with JMA Consultants, Inc. (JMAC). He was born in Osaka and graduated from Osaka Prefectural University. He joined JMAC in 1961 and became a senior consultant in 1977. His many fields of expertise include reducing manufacturing costs through the application of industrial engineering, the planning and design of new factories, the relayout of existing factories, and other areas related to improving manufacturing efficiency. He has also done extensive work in the field of logistics, including such areas as the reduction of distribution costs, the planning and design of distribution centers, and increasing the efficiency of distribution operations. He is the author of many books in Japanese, including *An Introduction to* Kaizen, *New* Kaizen *Techniques for Production Supervisors,* and *An Easy Introduction to Distribution* Kaizen. He has also presented papers at the International Logistics Conference held annually in Japan.

CHAPTER 4.3

WORK DESIGN AND FLOW PROCESSES FOR SUPPORT STAFF

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The techniques of work analysis and work design, as applied to both direct labor and indirect (overhead) labor, hold a well-established position in the long history of industrial engineering (IE) in the industrialized world. However, application of these techniques to the area of support staff has not yet been widely accepted. In this chapter, IE techniques, which have been cultivated through years of effort in many manufacturing settings, will be applied to the area of support staff, and procedures for the practical application of these techniques will be explained. As a foundation, the characteristics and functions of the support staff are first described. Then work analysis techniques, work standardization techniques, and techniques for designing new systems and organizations that fit the support staff situation are introduced.

THE LAG IN PURSUING EFFICIENCY IMPROVEMENT IN SERVICE WORK

In contrast to the employees of "direct work" departments, the work of the support staff does not directly contribute to company profitability. The main purpose of their business activity is to provide service, and this service can be thought of as professional assistance that enables other departments of the company to achieve higher profits.

Their work may be measured in terms of service contribution, and in general, such departments conduct their activity without sparing any effort. In the case of Japan's manufacturing industries, for example, technical support groups have long carried a heavy load and have made important contributions to the high productivity those companies have achieved.

Nevertheless, support staffs typically are not deeply concerned about service efficiency and in general their efficiency is low. It may even be said that while the operators of direct departments are always focused on process issues, support staff personnel attach importance to their "contribution."

To begin an examination of the productivity of support staff, it is important first to determine how their productivity should be measured. This can be expressed in the following formula;

$$\text{Support Staff Productivity} = \text{Services Contribution} \times \text{Service Efficiency}$$

In this chapter, techniques for improvement of service efficiency, a subject that has received little attention thus far, will be introduced. However, first a more detailed examination of the characteristics of the business activity of the support staff is necessary.

SPECIAL CHARACTERISTICS OF THE SUPPORT STAFF

While it is true that serious pursuit of efficiency in support staff business activity is long overdue, it cannot be said that there has been no activity at all. Today, many firms have launched efficiency improvement activities based on the application of computer systems. However, this is only one aspect of efficiency improvement, and the core issues of efficiency improvement have still not been touched.

Why has the serious pursuit of support staff efficiency been so long in coming? To answer this, the background of support staff must be considered and their problems identified. Our discussion focuses on the situation faced by Japanese companies, but many of the problems are common to companies in other countries, as well.

Inconsistency of Service Demanded and Offered

There can be significant inconsistency between the service demanded (expected results) of support staff and the service offered (due to situational constraints). The flow of support staff work, from the initiation of intellectual activity is somewhat reversed (see Fig. 4.3.1) compared with the flow for a manufacturing department. It shows the general relationship of input and output for intellectual activity, which in this case is the handling of business matters. In each module, there may be a discrepancy between the desired service content and the service content actually provided.

If this relationship is applied to the case of a manufacturing department, for example, the required service, or input, might be to build a product according to the specifications shown in the design drawings. The actual product built as a result of the manufacturing process would be the provided service, or output. In this case, if a discrepancy occurs in the relationship between input and output, a defective product results, which must be disposed of, and a new, correct product must be built. Consequently, in the manufacturing department activity is carefully controlled so that discrepancies are avoided, and the service required = service provided relationship is rigidly maintained.

In the business of the support staff, however, the relationship between these two aspects of service tends to become required service ≤ service provided. This formula shows that the service provided is in excess of the service required, which of course means inefficiency. Why does this tend to occur? One possible cause is that the definition of the service required is very vague. In manufacturing operations, if the designs and drawings are vague, good products will not be produced. In the case of support staff work, it is as though productive work starts while the required service (the equivalent of designs and drawings) is still unclear.

A Great Variety of Work Content

The role of support staff is to provide services that enable the activity of the direct departments to be done smoothly. However even though *service* can be expressed in a single word, in practice a variety of requirements must all be responded to, and this creates a situation where there is very little work of a highly repetitive nature. Support staff activity is composed of a combination of miscellaneous tasks, and it must be recognized that even each individual support staff employee must perform various kinds of work.

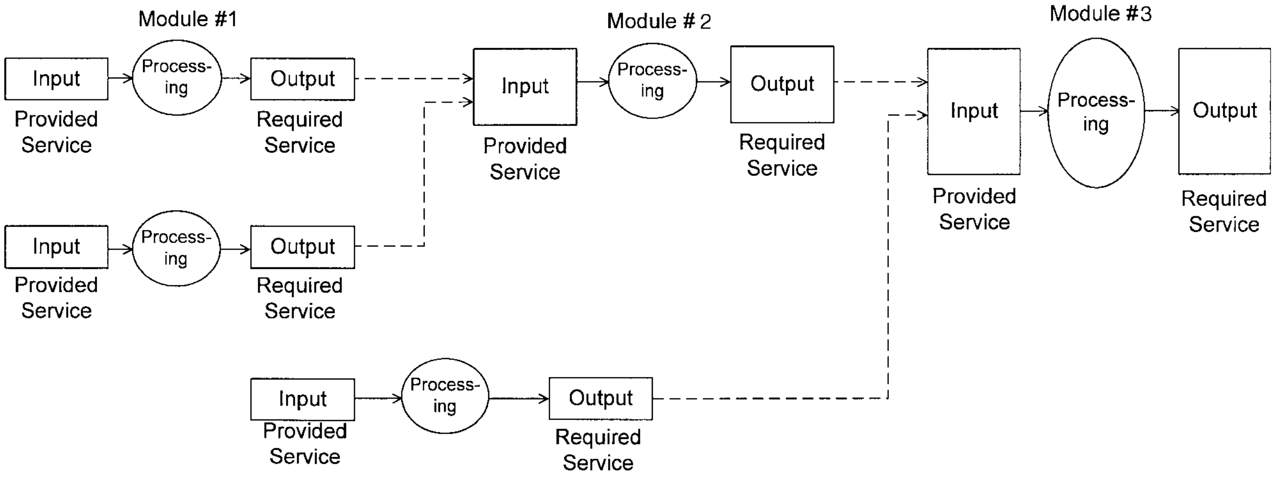
Module #1
Input
Provided Service
Process-ing
Output
Required Service
Input
Provided Service
Process-ing
Output
Required Service
Module # 2
Input
Provided Service
Process-ing
Output
Required Service
Input
Provided Service
Process-ing
Output
Required Service
Module #3
Input
Provided Service
Process-ing
Output
Required Service

FIGURE 4.3.1 Provided service and required service.

Because the work of the support staff is inherently different from the direct labor of the production department, it is important to apply techniques that recognize the uniqueness of support staff work when performing work analysis and work design in this area.

Many industrial engineering techniques have achieved excellent results in increasing the efficiency of direct labor. Several of those techniques have been adapted to the purpose of improving the efficiency of support staff work. It may be said that among the various branches of engineering, industrial engineering is the one that has treated human actions in a scientific and systematic way, and, moreover, it can be applied regardless of the specific field or type of human action being studied.

WORK ANALYSIS TECHNIQUES APPLIED TO SUPPORT STAFF (1)

The technique of work analysis (centered on work sampling) can be applied to support staff activities. Before application, the actual situation of the support staff business activity, which is complex and diversified, must be fully understood, both in terms of the purpose of actions and the content of actions.

The usual approach to work sampling is for a designated observer to periodically check certain operators and keep a record of their activity. However, in performing work sampling of support staff work (i.e., the whole activity of the support staff), this approach cannot be used. This is because to an observer watching a person performing support staff work, it may appear that the work content is always the same.

In this situation, a better method for conducting work sampling is for the person who is being studied to report exactly what it is that he or she is doing at the times of observation, according to some clear guidelines. Considering the purpose of observation, which is to create a profile of the work situation in terms of classes of activities, it is necessary to determine what is to be observed and by what method, prior to starting. The details of this preparation are described in the following sections as a sequence of four steps.

Step 1. Establishing the Activities to Be Studied. The employee being studied writes down, at previously specified times, the nature of the work he or she is performing at that moment. In doing so, it is necessary that the employee clearly indicate (1) what activity (content of activity) he or she is performing, and (2) for what purpose (purpose of activity = type of business function). Since the potential for improvement through better work design will focus on these two points, the criteria for classifying activity content and purpose of activity should be determined ahead of time and appropriate categories set.

Classification of Activity Content. Activity content can be defined by taking such activities as information gathering or information processing and breaking them down into subcategories. For example, information processing could be broken down further into calculating, summing-up, diagramming, or recording. Once such a classification scheme has been developed it will generally be applicable to support staff work at any company.

In classifying activity content, an effort should be made to select general classes that will have wide applicability (i.e., across a broad range of companies), as this will enable meaningful benchmarking. For special cases where additional refinement is needed, subcategories should be established (see Fig. 4.3.2.).

Classification of Purpose of Activity. There are cases where even though the content of two activities appears to be the same the purposes may be quite different. Therefore, it is essential that for each measurement, a clear statement of the purpose of the activity be obtained. In this way, through examination from the two viewpoints of purpose (what is the function of this business activity?) and content, the combined result clearly defines the work actually being done.

However, this criterion of purpose of activity does not have the same general applicability as the former activity content, and may be unique to each company. A sample classification scheme for purpose of activity is shown in Fig. 4.3.3.

Major classification	Subclassification
Information acquisition	Preparing materials, arranging Reviewing materials Searching for materials Other
Information processing	Calculating, processing data Diagramming, describing Checking Other
Meeting, interviewing	Customer meetings Internal (intracompany or intradepartmental) meetings Internal communications Other
Contacting	Internal telephoning External telephoning Other
Conferences	Internal to departments External
Various kinds of processing	Monitoring, measuring pollution Other
Other	Business trip, other out-of-office activity Free time Other

FIGURE 4.3.2 Activity content classification table.

Step 2. Preparing Survey Forms. As for the forms used in work sampling surveys, two kinds of formats should be prepared. One is a code table for observed data points, which is used by each person who is a subject of the study to select a code describing his or her work (the purpose and content of the activity) at the specified times. The other is a work sampling survey table into which the results of the (self-reported) observations are entered as data. The method for summarizing the results may be either batch processing or on-line.

Code Table for Observation Items. Codes are now selected to describe each of the observation items defined in the former step. The codes must be clear so that the personnel who are reporting on their own activities can easily choose the proper one. The codes are based on a matrix of activity content versus purpose of activity, as shown in Fig. 4.3.4. In the matrix, the purpose of the activity is indicated by a letter, while the content is shown by a two-digit number. If the only objective were the gathering of data to be processed, an all-numeric system would suffice. However, requiring operators to enter an alphanumeric combination helps them to track both purpose and content (i.e., according to column and row), thus reducing the chance of errors.

Work Sampling Survey Table. Figure 4.3.4 is an example of a work sampling survey table. Since the format of the survey table depends on how the computer summarization is done, this should be regarded simply as one example, intended to show the typical content of such a table.

Step 3. Performing the Work Sampling

Determination of Observation Period and Number of Observations. The number of observations needed depends on the intended purpose of the work sampling. If the purpose is a preliminary survey to grasp the general content and volume of business activity, a one-month period is desirable, and that could probably be done in practice with minimal disturbance. For the purpose of measurement of work quantity for establishment of standard times,

	Purpose of activity Activity content	Code No.	Planning (monthly)	Planning (weekly)	Confirm actual results	Production orders	Processing forms	Manage work in process	Cost management	Managing model (or part) numbers	Parts supply	Generate orders	Negotiate unit prices with subcontractor	Storage business	Create operation manual	General affairs										WSP	Others
			A	B	C	D	E	F	G	H	I	J	K	L	M	N	P	Q	R	S	T	U	V	W	X	Y	Z
Information Acquisition	Preparing of materials, Arranging	11	11A	11B	11C	11D	11E	11F	11G	11H	11I	11J	11K	11L	11M	11N	11P	11Q	11R	11S	11T	11U	11V	11W	11X	11Y	11Z
	Reviewing Materials	12	12A	12B	12C	12D	12E	12F	12G	12H	12I	12J	12K	12L	12M	12N	12P	12Q	12R	12S	12T	12U	12V	12W	12X	12Y	12Z
	Searching for materials	13	13A	13B	13C	13D	13E	13F	13G	13H	13I	13J	13K	13L	13M	13N	13P	13Q	13R	13S	13T	13U	13V	13W	13X	13Y	13Z
	Other	14	14A	14B	14C	14D	14E	14F	14G	14H	14I	14J	14K	14L	14M	14N	14P	14Q	14R	14S	14T	14U	14V	14W	14X	14Y	14Z
Information Processing	Calculating; processing data	21	21A	21B	21C	21D	21E	21F	21G	21H	21I	21J	21K	21L	21M	21N	21P	21Q	21R	21S	21T	21U	21V	21W	21X	21Y	21Z
	Diagramming, Describing	22	22A	22B	22C	22D	22E	22F	22G	22H	22I	22J	22K	22L	22M	22N	22P	22Q	22R	22S	22T	22U	22V	22W	22X	22Y	22Z
	Checking	23	23A	23B	23C	23D	23E	23F	23G	23H	23I	23J	23K	23L	23M	23N	23P	23Q	23R	23S	23T	23U	23V	23W	23X	23Y	23Z
	Other	24	24A	24B	24C	24D	24E	24F	24G	24H	24I	24J	24K	24L	24M	24N	24P	24Q	24R	24S	24T	24U	24V	24W	24X	24Y	24Z
Meeting, Interviewing	Internal (Intracompany or intradepartmental) meetings	31	31A	31B	31C	31D	31E	31F	31G	31H	31I	31J	31K	31L	31M	31N	31P	31Q	31R	31S	31T	31U	31V	31W	31X	31Y	31Z
	Internal communications	32	32A	32B	32C	32D	32E	32F	32G	32H	32I	32J	32K	32L	32M	32N	32P	32Q	32R	32S	32T	32U	32V	32W	32X	32Y	32Z
	Directing, Communicating	33	33A	33B	33C	33D	33E	33F	33G	33H	33I	33J	33K	33L	33M	33N	33P	33Q	33R	33S	33T	33U	33V	33W	33X	33Y	33Z
Contacting	Internal telephoning (company or department)	41	41A	41B	41C	41D	41E	41F	41G	41H	41I	41J	41K	41L	41M	41N	41P	41Q	41R	41S	41T	41U	41V	41W	41X	41Y	41Z
	External telephoning	42	42A	42B	42C	42D	42E	42F	42G	42H	42I	42J	42K	42L	42M	42N	42P	42Q	42R	42S	42T	42U	42V	42W	42X	42Y	42Z
Conferences	Internal to departments	51	51A	51B	51C	51D	51E	51F	51G	51H	51I	51J	51K	51L	51M	51N	51P	51Q	51R	51S	51T	51U	51V	51W	51X	51Y	51Z
	External to company or departments	52	52A	52B	52C	52D	52E	52F	52G	52H	52I	52J	52K	52L	52M	52N	52P	52Q	52R	52S	52T	52U	52V	52W	52X	52Y	52Z
Other	Free time (personal business or relaxation)	61	61A	61B	61C	61D	61E	61F	61G	61H	61I	61J	61K	61L	61M	61N	61P	61Q	61R	61S	61T	61U	61V	61W	61X	61Y	61Z
	Business trip, Out-of-office activity	62	62A	62B	62C	62D	62E	62F	62G	62H	62I	62J	62K	62L	62M	62N	62P	62Q	62R	62S	62T	62U	62V	62W	62X	62Y	62Z
	Other	63	63A	63B	63C	63D	63E	63F	63G	63H	63I	63J	63K	63L	63M	63N	63P	63Q	63R	63S	63T	63U	63V	63W	63X	63Y	63Z
	Various kinds of processing (Including direct work)	71	71A	71B	71C	71D	71E	71F	71G	71H	71I	71J	71K	71L	71M	71N	71P	71Q	71R	71S	71T	71U	71V	71W	71X	71Y	71Z

FIGURE 4.3.3 Survey code table (production planning section).

WORK DESIGN AND FLOW PROCESSES FOR SUPPORT STAFF

Section Code				Module No.			Gender		Date of Survey			Employee Number					Name			
							Male	Female	Month/Date											

Survey #	Code	Functional Division						Business Contents						Planned or other			OA	
		C		B		A		Routine		Judgment		Investigation, Plan	Others	Planned	Spot	Others	Possible	Not possible
		Basic	Auxiliary	Basic	Auxiliary	Basic	Auxiliary	Planned	Spot	Repetitive	Spot							
01		1	2	1	2	1	2	11	12	21	22	31	41	51	52	53	61	62
02		1	2	1	2	1	2	11	12	21	22	31	41	51	52	53	61	62
03		1	2	1	2	1	2	11	12	21	22	31	41	51	52	53	61	62
04		1	2	1	2	1	2	11	12	21	22	31	41	51	52	53	61	62
05		1	2	1	2	1	2	11	12	21	22	31	41	51	52	53	61	62
06		1	2	1	2	1	2	11	12	21	22	31	41	51	52	53	61	62
07		1	2	1	2	1	2	11	12	21	22	31	41	51	52	53	61	62
08		1	2	1	2	1	2	11	12	21	22	31	41	51	52	53	61	62
09		1	2	1	2	1	2	11	12	21	22	31	41	51	52	53	61	62
10		1	2	1	2	1	2	11	12	21	22	31	41	51	52	53	61	62
11		1	2	1	2	1	2	11	12	21	22	31	41	51	52	53	61	62
12		1	2	1	2	1	2	11	12	21	22	31	41	51	52	53	61	62
13		1	2	1	2	1	2	11	12	21	22	31	41	51	52	53	61	62
14		1	2	1	2	1	2	11	12	21	22	31	41	51	52	53	61	62
15		1	2	1	2	1	2	11	12	21	22	31	41	51	52	53	61	62

This form is designed for use in conducting work sampling of support functions. As each survey is made, at the designated random time, an entry is made indicating the type of activity the observed employee is engaged in. For example, a code entry of C1-22-62 would indicate basic function of type C, which is a function requiring judgment (rather than a routine function), being done on a spot basis (i.e., not a scheduled, repetitive activity) and which probably cannot be replaced through Office Automation (OA). For each department, the Functional Divisions would be defined. For example, in Human Resources, they might include recruiting, record maintenance, employee training, etc. These forms can be used for self work sampling also.

FIGURE 4.3.4 Example of a work sampling survey table.

a somewhat longer period will be necessary. Lengthening the period is not intended simply to increase the number of observations, but to avoid missing important but less frequently occurring work elements. Figure 4.3.5 illustrates a general theoretical formula for determining the number of work sampling observations necessary for a 95 percent accuracy level.

Determination of Random Observation Times. Although support staff work, unlike production line work, is not purely repetitive, it may be characterized by subtle *periodicity.* There-

$$N = \frac{4P(1-P)}{0.0025P^2} = \frac{4(1-P)}{0.0025P} = \frac{1600(1-P)}{P}$$

- N: Total number of observations = Number of observed personnel × Number of observation times per day × Number of days
- P: Occurrence ratio of major observation item

This formula is intended to produce observation results with a 95% reliability rating, and 5% relative error.

Example: P = 25%

$$N = \frac{4(1-0.25)}{0.0025 \times 0.25} = \frac{1600(1-0.25)}{0.25} = 4{,}800 \textit{ observations}$$

FIGURE 4.3.5 Calculation of required number of work sampling observations.

fore, in establishing the times for work sampling observations, it is important that random times be selected. This avoids the risk that periodicity in the sampling might coincide with a periodicity in the support staff work and lead to an unnatural weight being given to certain activities. To select the actual random times, a commonly available chart of random numbers is used. Figure 4.3.6 shows a sample of a random time schedule prepared for work sampling of support staff work.

Step 4. Summarizing Work Sampling Data and Analysis of Results. Figure 4.3.7 shows the result of work sampling done mainly to identify activity content. Based on these results, work analysis from the viewpoint of activity content can be done. In addition, the table characterizes the work done under each activity content category as to the proportion that is basic versus auxiliary, routine versus judgmental, and so on. Figure 4.3.8 shows the results of work sampling of a multidepartment organization, conducted mainly to determine purpose of activity.

WORK ANALYSIS TECHNIQUES APPLIED TO SUPPORT STAFF (2)

In the previous section, an analysis technique based on work sampling was shown. It is a useful technique for identifying and understanding problems. However, it is too coarse to apply at the stage of conducting improvement activities involving actual work design. Therefore, in this section an analysis technique designed to support actual improvement activity is described. First, however, a methods standardization technique, which is a prerequisite to work design, must be introduced.

The Technique of Method Standardization

To improve the methods currently being used, and to design new work methods, the four stages shown in Fig. 4.3.9 must be followed.

The first step is to identify current methods. In regard to the uniqueness of the support staff, current methods are variable in the case of support staff work, and the range of variation is quite broad. Nevertheless, work design and methods improvement must be approached systematically. Even though the current methods are dynamic, work design and improvement must be stable. Thus, the technique of method standardization is used to define a dynamic state in terms of a stable one, reducing it to a single model.

1		2		3		4		5		6		7		8		9		10	
Order	Time	Order	Time	Order	Time	Order	Time	Order	Time	Order	Time	Order	Time	Order	Time	Order	Time	Order	Time
8	8:02	18	8:11	5	8:05	11	8:41	21	8:14	8	8:05	3	8:04	19	8:28	12	8:01	22	8:03
19	8:28	3	8:41	11	8:17	17	9:00	22	8:39	14	8:17	11	8:44	20	8:36	2	8:23	16	8:15
12	8:31	14	8:53	15	8:43	4	9:15	9	8:53	18	8:43	21	8:50	12	8:44	6	8:41	21	8:55
9	9:04	4	9:00	13	9:01	20	9:57	8	9:30	16	9:01	7	9:18	16	9:20	16	9:12	20	9:36
21	9:41	9	9:24	17	9:49	5	10:11	11	9:45	2	10:09	19	9:37	6	9:35	11	9:32	15	9:47
22	10:01	17	10:22	2	10:08	21	10:38	4	10:22	5	10:13	14	9:49	1	10:15	8	10:06	6	10:07
4	10:40	16	10:33	4	10:23	15	10:30	20	10:33	20	10:47	5	10:04	3	10:36	18	10:10	3	10:19
18	10:51	8	10:47	20	10:36	1	11:08	13	11:16	7	11:016	13	10:31	10	10:56	14	11:06	5	10:55
1	11:16	1	11:01	6	11:20	14	11:22	16	11:29	9	11:20	16	10:55	5	11:32	13	11:15	19	11:10
6	11:41	5	11:54	9	11:29	9	11:35	2	11:58	12	11:34	10	11:40	11	11:59	15	11:28	8	11:29
14	13.28	13	13:28	19	13:52	8	13:06	1	13:12	1	13:34	17	13:27	2	13:05	19	13:38	1	13:40
11	13:58	7	13:54	12	14:39	18	13:27	6	13:22	6	13:45	18	13:56	9	13.46	7	14:37	4	14:01
16	14:13	22	14:04	7	14:49	10	13:58	19	14:04	10	14:10	1	14:28	13	13:50	17	14:48	9	14:19
5	14:33	10	14:57	3	15:13	7	14:19	14	14:16	3	14:56	2	14:48	21	14:05	10	15:00	7	14:43
20	14:45	17	15:04	22	16:06	22	15:01	3	14:52	19	15:02	12	14:52	17	14:30	4	15:24	17	15:25
2	15:12	15	15:50	14	16:25	19	15:20	12	15:24	13	15:12	6	15:23	18	14:38	22	15:44	18	15:34
15	15:30	19	16:11	21	16:32	3	15:48	10	15:46	15	15:22	22	15:38	14	15:15	4	16:01	13	16:15
7	16:11	6	16:31	18	16:49	13	16:02	17	16:10	11	15:30	15	16:07	8	16:19	21	16:29	11	16:45
17	16:30	11	17:14	10	17:06	16	16:31	15	16:34	4	15:49	8	16:12	4	16:27	20	16:50	12	17:10
10	16:56	21	17:26	8	17:33	2	17:07	5	17:05	21	14:34	9	16:27	7	16:30	9	16:53	10	17:18
3	17:05	2	17:35	1	17:45	12	17:27	18	17:26	17	14:45	20	17:07	22	17:29	3	17:35	14	17:25
13	17:28	20	17:58	16	17:53	6	17:38	7	17:53	22	17:22	4	17:19	15	17:45	1	17:56	2	17:48

This form provides a guide to observers assigned to do work sampling. Each day, 10 samplings are done in the morning, between 8:00 and 12:00, and 12 between 13:00 and 18:00. Each day (day 1, day 2, etc.) the samplings are done at the times specified for that day, which are designed to ensure randomness. Moreover, 22 orders for performing the sampling have been established. These orders would be defined in a separate sheet, which in a workplace with 6 operator stations, might indicate: order 1: B-F-C-D-A-E, order 2: C-E-F-D-B-A, etc. Varying the observation order in this way also improves data accuracy by eliminating the case where stations E and F, always being the last, are alerted to the approach of the observer and thus always increase their work pace at the moment of observation to higher than normal.

FIGURE 4.3.6 Work sampling random time table.

(Unit %)

Activity Content Classification			Function Classification		Business Classification								Possibility of Office Automation (OA)
Major Classification	Code Subclassifications	Data distribution (total=100)	Basic	Auxiliary	Routine			Judgment			Survey (including planning)	Other	
					Planned	Spot	Total	Planned	Spot	Total			
Information collection	Arrange material	3	11	89	56	25	81	3	8	11	4	5	6
	Review material	2	29	71	24	26	50	8	22	30	11	10	3
	Search for materials, etc.	1	10	90	22	38	60	4	18	22	3	14	5
	Subtotal	6	17	83	40	27	67	5	14	19	6	8	5
Information processing	Receive, compare, sort	9	68	32	81	9	90	6	3	9	0	0	14
	Calculate, process	10	85	15	81	12	93	3	3	6	1	1	54
	List, describe, consider	21	82	18	51	15	56	12	15	27	6	1	22
	Check	6	78	22	37	10	47	38	13	51	1	0	8
	Process using EDP or WP machine	8	79	21	73	14	87	2	8	10	1	1	40
	Operate copier or fax machine	2	17	83	52	31	83	1	8	9	1	6	24
	Other	1	30	70	50	20	70	2	21	23	0	6	2
	Subtotal	57	77	23	63	13	76	10	10	20	3	1	27
Meeting/Interviewing	Meet customers	7	82	18	18	11	29	47	18	65	2	4	0
	Meet internally (with dept. or company)	7	53	47	10	27	37	7	36	43	9	11	2
	Give directions or communicate internally	1	64	36	18	17	35	15	43	58	5	3	1
	Subtotal	15	66	34	14	19	33	25	29	54	6	7	1
Meeting (telephoning)	Internal telephoning	2	46	54	15	24	39	7	42	49	5	8	1
	External telephoning	3	49	51	15	26	41	13	36	49	3	7	0
	Subtotal	5	48	52	15	25	40	10	38	48	4	7	1
Confer-ences	Meetings internal to dept.	2	34	66	13	18	31	21	25	46	12	10	0
	External meetings	1	81	19	8	10	18	34	34	68	7	7	0
	Subtotal	3	41	59	13	17	30	23	26	49	12	10	0
Other Tasks	Monitoring, measurement	0	75	25	30	20	50	12	30	42	6	1	14
	Other	2	39	61	47	24	71	12	10	22	0	7	11
	Subtotal	2	46	54	43	24	67	12	14	26	1	6	12
Other	Lecture, Study, Training	1	9	91	1	46	47	20	7	27	3	22	0
	Business trip, Going out	3	55	45	15	16	31	11	42	53	4	12	1
	Free time	2	0	100	0	0	0	0	0	0	0	100	0
	Other	5	4	96	34	19	53	1	3	4	0	42	6
	Subtotal	12	17	83	20	18	38	5	13	18	1	42	3

This format is used for displaying the results of a work sampling survey. The subtotals summarize how the observed employee utilizes his or her time, on average: 6% for information collection, 57% for information processing, etc. Activity under each major and minor classification is further divided between basic (value adding) functions and auxiliary functions. Activity is also broken down into four main categories: routine, (requiring) judgment, survey/planning, or other. Finally, an estimate is made of what portion of each subactivity lends itself to office automation.

FIGURE 4.3.7 Work sampling statistical table 1.

(Survey period :   )   (Unit: %, except as noted)

	Code / Module	10 General business		20 Human resources		30 Materials		40 Purchasing		50 Accounting	
	Personnel involved	10 (people)		12		10		8		11	
	Number of observations	1,450 (observations)		2,640		1,450		880		1,174	
	A	Budgeting	1	Organization of office	0	Accounts payable	9	Select vendors	55	General accounting	17
	B	Documents	16	Personnel	24	Processing forms	30	Contract	29	Calculating costs	35
	C	General company business	25	Labor-management relationship	4	Budgeting	0	Management of materials	4	Managing funds	8
	D	Legal work	3	Instruction and training	4	Planning information	2			Revenues and expenditures (accounting)	20
	E	Real estate-related	4	Payroll	21	System management	5			Sales accounting	7
	F	Maintenance/repair	4	Welfare and benefits	14	Stock management	26			Foreign exchange	1
	G	Security	2	Systems	8	Disposal of excess stock	0			Budgeting	0
	H	Publicity	30	Forecasting	0	Acceptance of vendor work	10			Administration of property	2
	I			Safety	7					Subsidiary company issues	2
	J			Hygiene	2					Taxation issues	0
	K			Environmental pollution	4					Audits	0
	L									Revision of company accounting rules	0
	M									Investment and financing	0
	N									Stock-related	0
	O, P, Q										
Common items	R (Work Simplification Program)		3		2		1		1		1
Materials submitted	External (Inspection) S				1						1
Materials submitted	External (Others) T										1
Materials submitted	Internal U				1						1
Common items	Others V		12		8		17		11		4
	Total		100		100		100		100		100

Note: In some cases, total is not 100% due to rounding off.

This table summarize one part of the results of a work sampling program that covered all the support departments of a company. This page shows what portion of their work time the personnel of each department (considered as a group) spend on each assigned activity. (Other tables would summarize the other information gathered, such as the allocation of work time between basic vs. auxiliary functions.)

FIGURE 4.3.8 Work sampling statistical table 2.

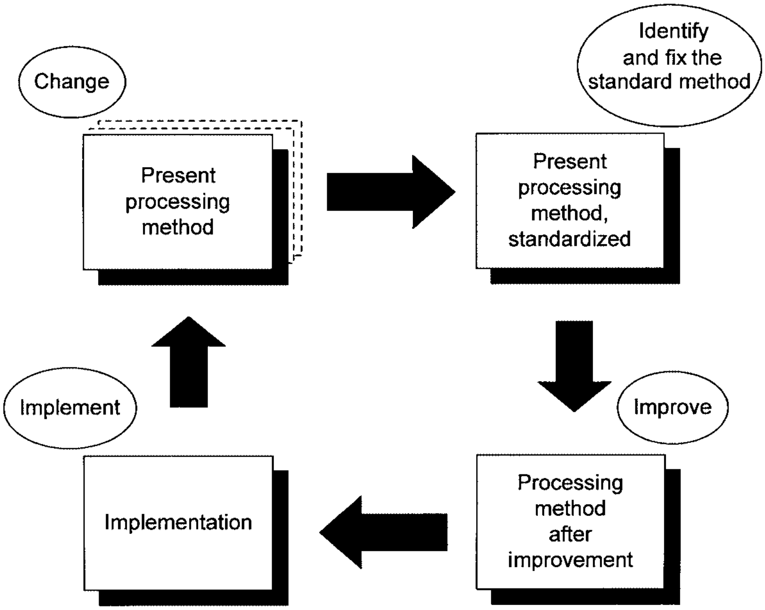
Change
Identify and fix the standard method
Present processing method
Present processing method, standardized
Implement
Improve
Implementation
Processing method after improvement

FIGURE 4.3.9 The four stages of method standardization and improvement.

This technique is used in the second stage of Fig. 4.3.9, standardizing the current methods. Even though the range of variation of current methods is large, standardization consists of adopting the pattern that appears most frequently, or in the case of support staff, is the most desirable (or reasonable) pattern among the current methods. Standardization entails extracting the actual task or process from the observed work content, identifying the task or process time—work unit (WU)—for each business activity, and measuring the number of times a business activity occurs—work count (WC).

In proceeding with this standardization, the following practices should be considered:

- Describe the typical, frequently appearing pattern.
- Do not include unusual cases.
- Describe current methods in the ideal form: the one best way.

Once the current methods have been standardized, the activities of work design and work improvement aim to discover and introduce various changes resulting in a higher level of productivity or performance. Appropriate work analysis, making full use of accepted techniques, is thus an essential preliminary step in improvement activities.

The Techniques of Work Analysis

The following is a detailed sequential explanation of the steps in a work analysis.

Step 1. Drawing a Block Diagram to Understand the Work Content. It is important to determine just how finely tasks need to be classified to analyze or understand the content of a business activity. For most purposes, classification of an activity according to the following eight levels provides adequate information: (1) overall corporate results, (2) department or section, (3) function, (4) activity, (5) process, (6) operation, (7) element, and (8) motion.

In the case of work analysis of support staff work, performing analysis at the three levels of function, activity, and process is a practical approach. Before proceeding to detailed analysis, the work content of the company section being studied is analyzed at the function level and the results are shown in a block diagram. This chart permits a company to

- Map on a macro level the entire flow of the business activity and prevent any oversights in the analysis of the work.
- Identify the mutual relationships between various business activities.

An example of a block diagram is shown in Fig. 4.3.10.

Figure 4.3.10 shows the many functions of the General Affairs Department of a large company. The connecting lines indicate relationships between functions. For example, the functions of reviewing attendance records, evaluating employee performance, determining rewards or disciplinary action, and maintaining a viable relationship with the labor union are all interrelated. Using block diagrams like this, the detailed work analysis is performed in Step 2.

Step 2. Performing Detailed Work Analysis

Creating a Survey Table for a Standardized Model of Current Situation. From the functions that are entered in the block diagram, work content is analyzed here in even finer detail, down to the levels of activity and process. A typical form used as a survey table for standardized model of current situation is shown in Fig. 4.3.11. At this stage, the connection from section to activity to process—the structure of the work—becomes clear. Next, the *amount* of work is standardized for each business function that has been thus broken down into components. In quantifying (standardizing) the amount of work, the following formula is used:

$$\text{Amount of Work} = \text{WU (work unit)} \times \text{WC (work count)}$$

Determining Work Count. In order to determine work count, the frequency of occurrence of the task is analyzed on a per-month or per-week basis. In the case of support staff, it is necessary to conduct the survey of work amount using a year as one cycle. In addition, work content should be broken down into routine monthly tasks and specific monthly tasks (work that is done only in a certain month).

Establishing Work Units. In establishing work units, it is impractical to apply normal work measurement methods. Instead, for both work unit and work count, the support staff themselves must be relied on to self-report and provide data on their activities. However, accuracy problems always occur with self-reporting. Thus, to prevent confusion on the part of the self-reporting person about data entry decisions, it is good to adopt the representative value selection method as the method of self-reporting. A representative value selection method based on frequency and time values, and classified into one of three classes: (1) mode value (M), (2) optimistic value (O), and (3) pessimistic value (P), is convenient because it can be used for both work unit and work count.

This classification does not rate performance levels as average, minimum, or maximum, but instead focuses on standardizing the current methods. In other words, if an employee performs work according to the one best way (defined during the standardization step), then within an overall range (set by eliminating any abnormal data points), M is the most frequently occurring time value, O is an optimistic time value, and P is a pessimistic time value. A conceptual diagram of OMP is shown in Fig. 4.3.12.

Actual selection of representative values begins by designating the three classes of time values for work unit as To, Tm, and Tp, and the three classes of frequency values for work unit as Co, Cm, and Cp. Then, the most appropriate value, the representative value, for work unit is determined according to the following formula:

$$\text{WU: the selected representative value for T (time value)} = \{(\text{To} + 2\,\text{Tm} + \text{Tp})/4\} \times \text{(correction coefficient for one best way)}$$

$$\text{WC: the selected representative value of C (frequency)} = (\text{Co} + 2\,\text{Cm} + \text{Cp})/4$$

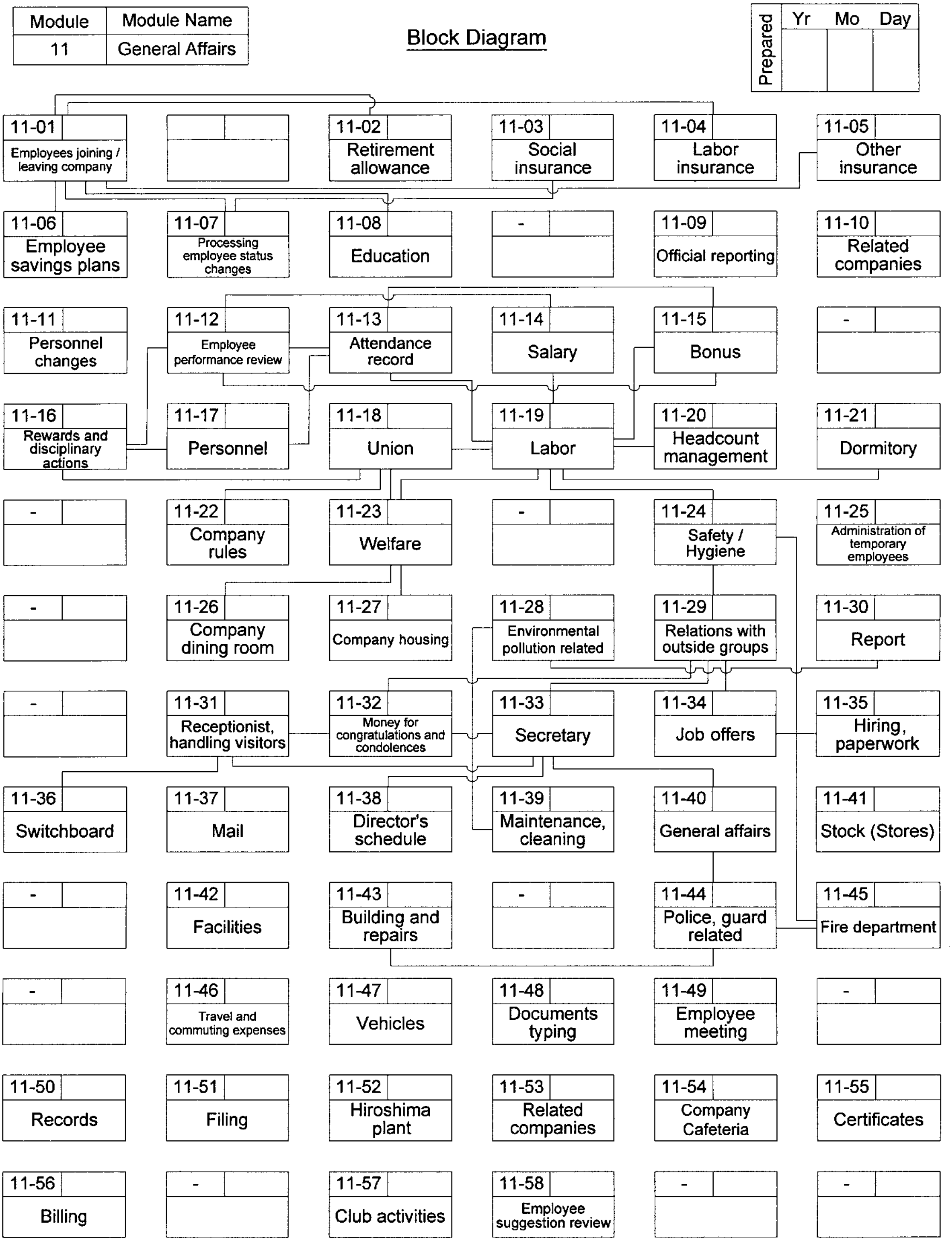
Module
Module Name
11
General Affairs
Block Diagram
Prepared
Yr
Mo
Day
11-01 Employees joining / leaving company
11-02 Retirement allowance
11-03 Social insurance
11-04 Labor insurance
11-05 Other insurance
11-06 Employee savings plans
11-07 Processing employee status changes
11-08 Education
-
11-09 Official reporting
11-10 Related companies
11-11 Personnel changes
11-12 Employee performance review
11-13 Attendance record
11-14 Salary
11-15 Bonus
-
11-16 Rewards and disciplinary actions
11-17 Personnel
11-18 Union
11-19 Labor
11-20 Headcount management
11-21 Dormitory
-
11-22 Company rules
11-23 Welfare
-
11-24 Safety / Hygiene
11-25 Administration of temporary employees
-
11-26 Company dining room
11-27 Company housing
11-28 Environmental pollution related
11-29 Relations with outside groups
11-30 Report
-
11-31 Receptionist, handling visitors
11-32 Money for congratulations and condolences
11-33 Secretary
11-34 Job offers
11-35 Hiring, paperwork
11-36 Switchboard
11-37 Mail
11-38 Director's schedule
11-39 Maintenance, cleaning
11-40 General affairs
11-41 Stock (Stores)
-
11-42 Facilities
11-43 Building and repairs
-
11-44 Police, guard related
11-45 Fire department
-
11-46 Travel and commuting expenses
11-47 Vehicles
11-48 Documents typing
11-49 Employee meeting
-
11-50 Records
11-51 Filing
11-52 Hiroshima plant
11-53 Related companies
11-54 Company Cafeteria
11-55 Certificates
11-56 Billing
-
11-57 Club activities
11-58 Employee suggestion review
-
-

FIGURE 4.3.10 Block diagram example.

Module name

Basic	1
Auxiliary	2

Module No.	Personnel code

Department: Section: Subsection:

Head of section

Filled in by

Activity		Present function	B.No				WU (minutes/cycle)			Time of occurrence (month)								WC (cycles/week)												APT
				A.No														First week			Second week			Third week			Fourth week			
Process	Reporting Unit		11	13	P.No 15	Function classification 17	To 18	Tm 21	Tp 24	E1 27	2 3 29	4 5 31	6 7 32	8 9 35	10 37	11 39	12 41	Co 43	Cm 46	Cp 49	Co 52	Cm 55	Cp 58	Co 61	Cm 64	Cp 67	Co 70	Cm 73	Cp 76	
										E 1	2 3	4 5	6 7	8 9	10	11	12													
										E 1	2 3	4 5	6 7	8 9	10	11	12													
										E 1	2 3	4 5	6 7	8 9	10	11	12													
										E 1	2 3	4 5	6 7	8 9	10	11	12													
										E 1	2 3	4 5	6 7	8 9	10	11	12													
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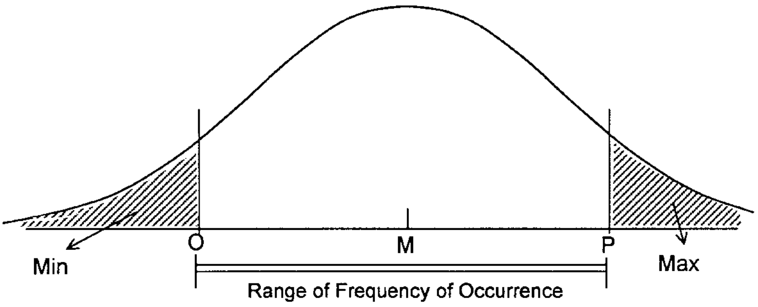
										E 1	2 3	4 5	6 7	8 9	10	11	12													
										E 1	2 3	4 5	6 7	8 9	10	11	12													
										E 1	2 3	4 5	6 7	8 9	10	11	12													

FIGURE 4.3.11 Survey table for standardized model of current situation.



O = Optimistic value of occurrence frequency

M = Most frequent occurrence

P = Pessimistic value of occurrence frequency

FIGURE 4.3.12 Concept of OMP.

Determination of APT. Allowed processing time (APT) is the time period allowed for each individual task to be completed. APT is an elapsed time measure and as such must be completed by the end of the month, rather than a consumed time measure that requires x hours to do. The greater the APT value is, the more "elasticity" there is as to exactly when the task can be accomplished; the smaller the APT value, the less the elasticity. In practice, with the exception of special cases, the typical APT in clerical departments is set at one week, while for other support staff departments, one month is generally selected. Design engineers of the Engineering Department, however, sometimes use one-year APTs.

Looking at the case where the APT for completing a task is a fixed time—for example, if the APT is one month—then that is converted to minutes as follows: 21 days (average number of days at capacity per month) × 8 hours (the stipulated number of working hours per day) × 60 minutes = 10,080 minutes. By using this APT, the amount of work signified by the number of people required (conversion to manpower requirements) can be calculated.

This is called the balancing factor (BF) and is used in the later step of work design.

$$BF = \Sigma(WU \times WC \div APT)$$

For example, for a task that takes 30 minutes to complete and occurs five times a month, the BF of the task is 30 minutes × 5 times ÷ APT (10,080 minutes), which is the workload of 0.0149 employees.

Establishment of Model Month (Week) to Become the Object of Improvement Activities. From the results of work analysis of support staff work, the work content and amount of work in a month or a year become clear. However, even if the objective of work analysis is accomplished, it is necessary to decide which month or week is to be used as the model (or baseline) in proceeding with work design improvement activities. After establishing the model month (week), work design can be performed on the basis of this model.

Figure 4.3.13 shows a method of selecting the model month (week) to become the target of improvement activities. In this case, the fourth week in April was chosen as the model, and it indicated a workload of 9.72 people. Based on these data, which were provided through the application of work analysis techniques, the next process, work design, can begin.

WORK DESIGN AND FLOW PROCESSES FOR SUPPORT STAFF

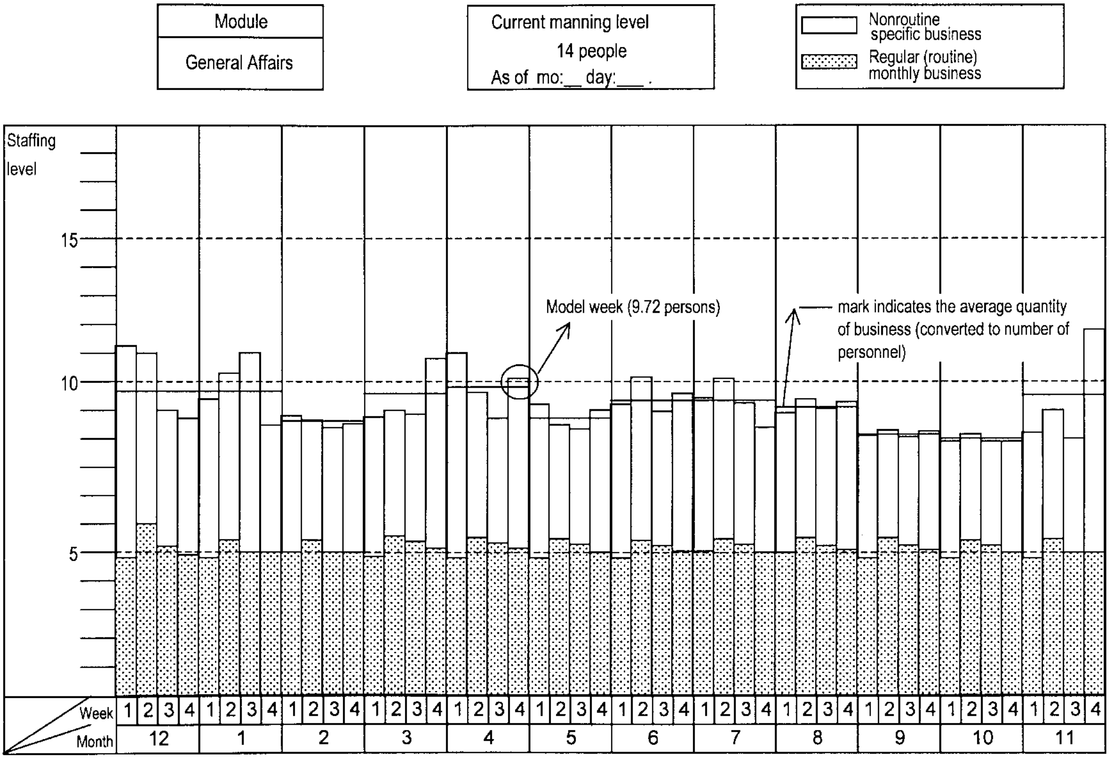


FIGURE 4.3.13 Selection of model week (or month).

WORK DESIGN APPLIED TO THE SUPPORT STAFF

Defining Work Output

When designing a work system using the design approach, the most important step is to define the work output that is to be the object of the improvement activities. This output can also be regarded as the essential function that the work is intended to accomplish.

This relationship is shown conceptually in Fig. 4.3.14, and the output in this case is the information and service that the work (i.e., the work that will be the target for improvement) should produce. Of course, it is necessary to define in the same way the input required for this output. In this relationship between input and output, work is the activity that converts input into output.

In defining output it is important to note that whereas manufacturing output can be clearly expressed in design drawings and other concrete representations the output of support staff work must be expressed in words. Furthermore, there is a tendency for output to be defined by considering the content of the business activity as currently performed, but this is not sufficient for a systematic definition of output according to the design approach.

To be more objective, special effort should be put into developing descriptions so that the output is accurately conveyed through full use of nouns, adjectives, and verbs. As a concrete example of defining output, the workplace of a facilities/equipment engineering staff is shown. The definition of the performance output for that technical staff would consist of several factors:

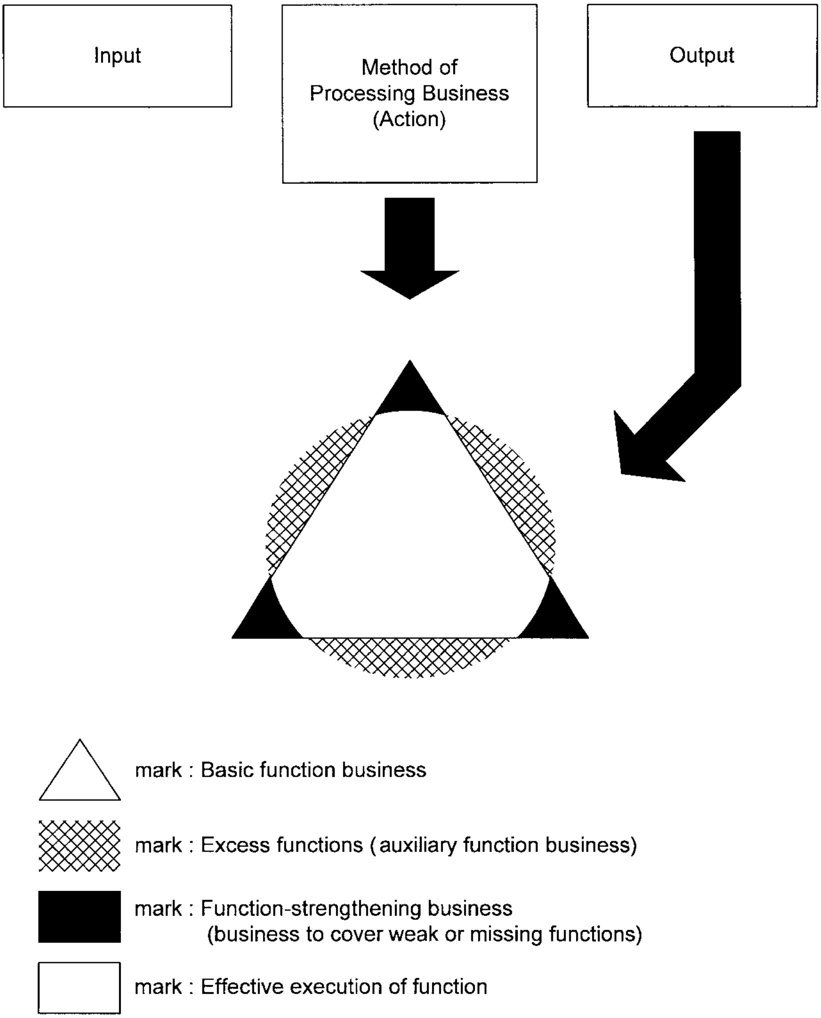

Input
Method of Processing Business (Action)
Output
mark : Basic function business
mark : Excess functions (auxiliary function business)
mark : Function-strengthening business (business to cover weak or missing functions)
mark : Effective execution of function

FIGURE 4.3.14 Design of business processing methods.

1. Design X equipment according to the specifications.
2. Build or procure X equipment according to the specifications.
3. Check and accept X equipment according to specifications.
4. Provide an operation manual for the accepted equipment.
5. Provide technical guidance and instruction regarding operation and troubleshooting of the equipment.
6. Handle repair and remodeling of the equipment where design changes are involved.
7. Acquire knowledge about new technologies.
8. Provide daily quality assurance for equipment.
9. Establish standard values and baselines for automated equipment.
10. Manage the record books for equipment after they become fixed assets.

WORK DESIGN AND FLOW PROCESSES FOR SUPPORT STAFF

Function Analysis and Establishment of Improvement Targets

Standardization of current methods was completed through the work analysis shown in Fig. 4.3.11, and through the step just described, work output has been defined. Now, functional analysis of the current (standardized) methods can be started. This is done by first describing or defining the current function, which was introduced as part of work analysis in Fig. 4.3.11. Breaking the work down to the level of activity will probably provide adequate detail for examining this work. The activity is then defined by the purpose it fulfills; attention to accurate description is essential, just as defining output was.

After finishing this stage, analysis of functions begins. The term *function analysis* as used here means to (1) analyze the output of the workplace that is the object of the improvement study and (2) examine the relationship between its current functions, broken down to the activity level through work analysis. Through this process at the activity level, functions can be classified as either basic (value-adding) or auxiliary.

After the analysis of activity-level functions and their classification as either basic or auxiliary functions is complete, the same analysis and classification are performed at the more detailed level of the processes that make up the activity. Here, processes that make up functions that were classified as auxiliary at the activity level, are automatically designated auxiliary functions. On the other hand, some of the processes that make up functions that were classified as basic functions at the activity level may be classified as auxiliary when examined after this finer breakdown.

Functions that were classified as basic when examined at the activity level received that classification because they have a direct impact on the output of the activity. However, at the process level, each individual process must undergo function analysis. The analytical path for classifying functions as basic or auxiliary is shown in Fig. 4.3.15.

After the function analysis is completed, but before work design is begun, evaluation measures for improvements proposed through work design must be clarified. There are two kinds of evaluation indices that can be established: one is expressed as work efficiency (e.g., how much productivity is improved) and the other is measured by qualitative improvement of the business function—the extent to which, after redesign, the function is done in a better, more effective way. (This latter concept can be expressed using an index that measures a high proportion of basic functions and less auxiliary functions that do not directly add value.)

The evaluation index of improved business efficiency (productivity improvement) is measured by the degree of improvement, which is calculated as degree of improvement (potential) = present number of people − the number of people required for basic functions. An example of calculating the degree of improvement is shown in Fig. 4.3.16.

This example in Fig. 4.3.16 is for one section within a company's Department of General Affairs. In this case, the function was being performed by 14 employees, but as a result of work analysis, it was found that the actual work amount was equivalent to just 10.3 people. And, after function analysis, it was further revealed that the work amount of 10.3 people was composed of basic function work equivalent to only 3.4 people, while the remaining work, equivalent to 6.9 people, was all auxiliary functions. Thus, in undertaking work design, an improvement target could be calculated by degree of improvement: potential degree of improvement = present number of people (14 people) − basic function work (3.4 people) = equivalent of 10.6 people. Therefore, work design should attempt to create a new structure whereby the company can accomplish the same activity with approximately 10 fewer people.

In improving business process methods, the ultimate goal is to reach the state where auxiliary functions are zero, which would represent achieving 100 percent of the improvement potential. However, this is an ideal goal. In most cases, actual improvement of 80 percent of the potential is considered good. Accordingly, the evaluation measure may be set at 80 percent of potential degree of improvement.

Next, in regard to the work design objective of qualitative improvement of business functions, the design concept should be to maximize the proportion of basic functions compared to auxiliary functions. With this in mind, work design should be initiated with the objective of achieving a ratio of 80 percent basic function work and 20 percent auxiliary function work.

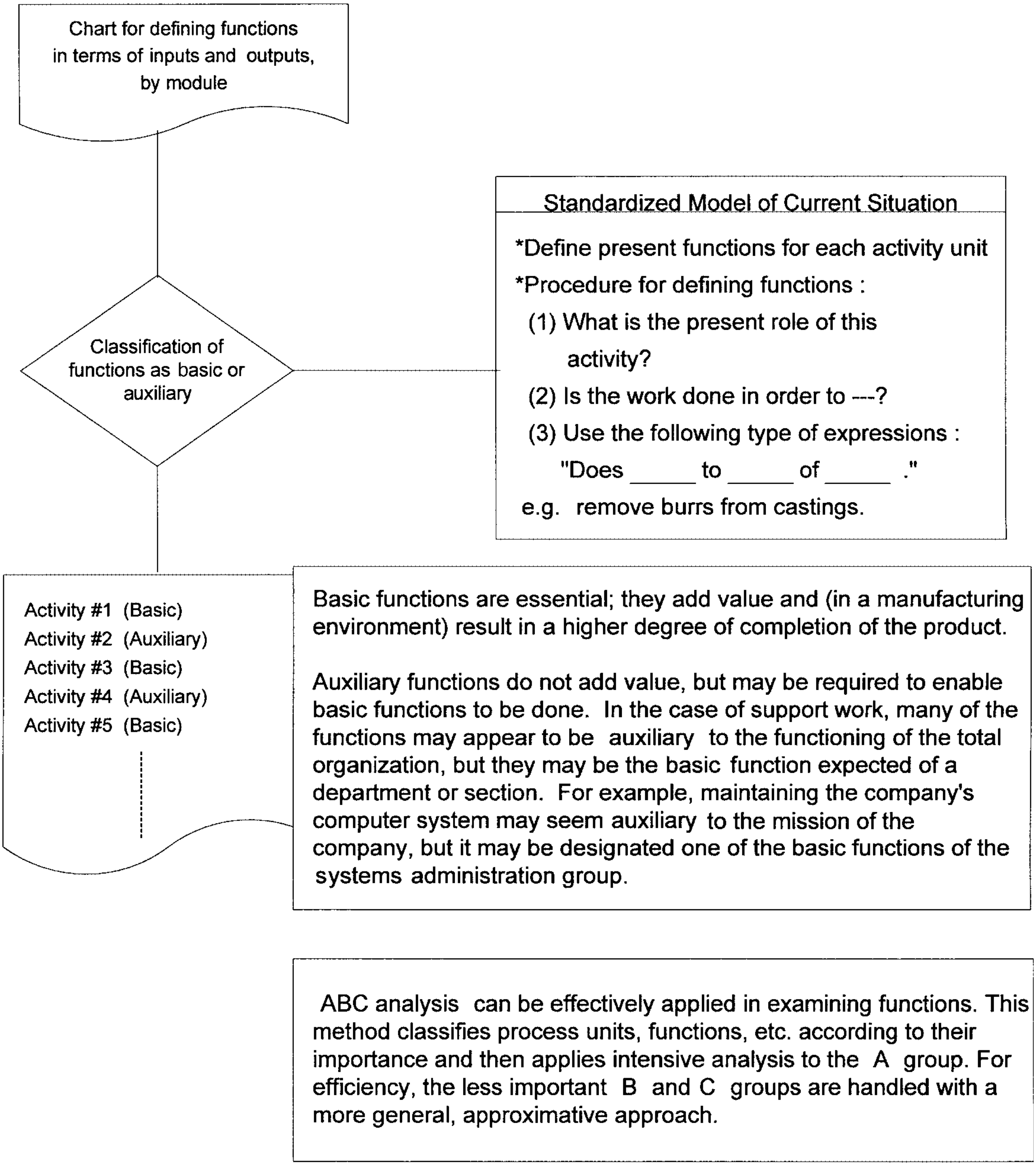


Chart for defining functions in terms of inputs and outputs, by module
Classification of functions as basic or auxiliary
Activity #1 (Basic)
Activity #2 (Auxiliary)
Activity #3 (Basic)
Activity #4 (Auxiliary)
Activity #5 (Basic)

Standardized Model of Current Situation

*Define present functions for each activity unit

*Procedure for defining functions :

(1) What is the present role of this activity?

(2) Is the work done in order to ---?

(3) Use the following type of expressions :

"Does _____ to _____ of _____ ."

e.g. remove burrs from castings.

Basic functions are essential; they add value and (in a manufacturing environment) result in a higher degree of completion of the product.

Auxiliary functions do not add value, but may be required to enable basic functions to be done. In the case of support work, many of the functions may appear to be auxiliary to the functioning of the total organization, but they may be the basic function expected of a department or section. For example, maintaining the company's computer system may seem auxiliary to the mission of the company, but it may be designated one of the basic functions of the systems administration group.

ABC analysis can be effectively applied in examining functions. This method classifies process units, functions, etc. according to their importance and then applies intensive analysis to the A group. For efficiency, the less important B and C groups are handled with a more general, approximative approach.

FIGURE 4.3.15 Flow of analysis for determining basic or auxiliary functions.

Module: General Affairs **Subject month:** November

Present staffing level
Number of people
14
100%

Model			Potential for Improvement
Basic	Auxiliary	Total	
people required	people required	people required	Number of people
3.4	6.9	10.3	10.6
24%	49%	74%	76%

The total theoretical potential for improvement of productivity is the amount by which the present staffing level exceeds the labor required for accomplishing basic functions only. In theory, all other work could be eliminated.

FIGURE 4.3.16 An example of calculating potential for improvement.

The Work Design Steps of Basic Design and Detailed Design

Basic design aims at planning the framework for new methods of processing business activities. Therefore, the subject for design is the basic function work as identified in the standardized model of the current methods.

In the case of the Department of General Affairs shown in Fig. 4.3.16, basic design is done for the basic function work, which corresponds to the work of 3.4 people. In designing the basic function work, the four principles of improvement, ECRS, are applied—except E (eliminate) because basic functions, by definition, cannot be eliminated. The principles of improvement include:

E: Eliminate
C: Combine
R: Rearrange
S: Simplify

E (eliminate) is not used because the functions being redesigned at this stage have already been determined to be basic (that is, essential to accomplishing the required output) at the earlier stage of function analysis. If such basic functions were eliminated here, complete reconsideration of the defined outputs would become necessary.

In doing basic design, the fundamental goal is to design the workload so that each person is assigned basic function work to the level of 0.8 of a person's capacity. For example, where there was basic function work for 3.4 people, the calculation becomes 3.4 people ÷ 0.8 = 4.25 people. Therefore, the framework of the basic design aims to accomplish the work with 4 to 5 people. However, if under the present work system, there is auxiliary function work for 6.4 people, the proposed basic design based on 4 to 5 people will be impossible to implement. In such cases, at the later stage of detailed design, it may be necessary to improve the work system.

If the framework of the basic design requires 5 people, then 5 people – basic function work (equivalent to 3.4 people) = 1.6 people. That is, if a system can be designed with just 1.6 people's worth of auxiliary functions, an ideal work design can be achieved. However, in this example, the current methods include auxiliary function work requiring 6.9 people. Clearly the work system must be improved to reduce auxiliary function work. Without such improvement, 6.9 people – 1.6 people = a shortage of 5.3 people; the work cannot be accomplished with only 5 people.

Therefore, at the detailed design stage, improvement ideas capable of reducing auxiliary function work by approximately 5.3 people are necessary. In such a case, improvement activity cannot be approached arbitrarily; creativity must be stimulated to seek ways of reducing auxiliary functions by an amount equivalent to 5.3 people. However, creativity is in limited supply, and it is not always possible to achieve objectives like this. When auxiliary function work cannot be improved sufficiently the first time, thorough examination may be repeated and redesign attempted.

In the example of the Department of General Affairs presented in Fig. 4.3.16, through improvements conceived at the final stage of detailed design, it was possible to design a new work system that enabled the work to be accomplished with 5 or 6 people in the final stage of detailed design.

The design approach style of work design is responsible for achieving excellent results like this, which show an unexpectedly high level of improvement compared to the previous situation. Conventional methods, which typically seek incremental improvements to an existing situation, rarely produce results comparable with those of a design philosophy that accepts no initial constraints and aims at achieving the ideal.

For example, if the same situation of work being done by 14 people were tackled using the conventional research approach, even if a 50 percent reduction in headcount were achieved, the concept of accomplishing the work with only ⅓ the number of personnel would probably never be considered. In pursuing improvement in work systems, trying to discover problems only in a readily visible current situation has limitations. It is more effective to use the design approach, which automatically reveals hidden problems; *with problems, nonrecognition is the biggest problem.*

For practical application, the middle approach, between the design approach concept presented in Gerald Nadler's *Work Systems Design: The IDEALS Concept* and the research approach, may be most appropriate. To be specific, it is not good to start from either a theoretical ideal system, like the IDEALS Concept, or an extreme ideal system—nor is it good to start from the existing system itself. Instead, starting from the middle ground, the basic concept of which might be described as a technologically workable IDEAL system, or TWIS, may provide the most effective approach.

CONCLUSION: CONTINUING WORK IN THE FIELD OF SUPPORT STAFF

It seems unavoidable that the descriptions presented in this chapter are wrapped in the context of Japanese companies and Japanese culture, but the issues apply similarly to businesses all over the world. The definition of *support staff* may vary slightly from country to country, but if the targeted work areas and the objectives are clearly identified, the author is confident that the TWIS approach is both practical and effective in dealing with real situations. Many Japanese companies have applied this approach. In the beginning of this chapter, we explained that the support staff is typically more interested in service contribution than in the efficiency of their own operations; whatever improvement activities they undertake generally focus on improving service quality, rather than efficiency. For that reason, this chapter focused on the often overlooked subject of service efficiency.

WORK DESIGN AND FLOW PROCESSES FOR SUPPORT STAFF

However, a big problem remains in regard to the support staff. This is the question of how to evaluate the productivity of support staff work. Few issues have been clarified in that regard, and should provide a fruitful field for further study.

BIOGRAPHY

Takenori Akimoto graduated from the Chiba University of Industrial Science in 1968 with a degree in industrial management. He joined JMA Consultants, Tokyo, in 1969 and became a chief consultant in 1976. After achieving the rank of senior consultant in 1987, he became head of the Advanced Industrial Engineering Department in 1996. He was appointed to the board of directors in 1999. He is the author of *An Introduction to Work Simplification Programs* and the coauthor of the *Manual for Applying Office Productivity Technology* (both in Japanese). Much of his career has been devoted to introducing techniques of work measurement and predetermined time standards (such as the MOST system) to Japanese industry.

Source: MAYNARD'S INDUSTRIAL ENGINEERING HANDBOOK

CHAPTER 4.4

SETUP TIME REDUCTION

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The changing world economy has caused an increase in the use of just-in-time manufacturing, which results in a trend toward short-run, multiple-product manufacturing. The frequent product changeovers make it imperative to improve setup operations and shorten line changeover times. In this chapter, various techniques for improving setup operations are introduced, such as making a distinction between *internal* setup tasks, for which production equipment must be stopped, and *external* setup tasks that permit equipment to continue to run. The target of single setup, or reducing setup time to less than 10 minutes is shown to be achievable in many situations. The concept of applying setup improvement techniques to administrative/support business and to management functions is discussed and examples of effective applications are shown.

INTRODUCTION

The bursting of the Japanese "bubble" of economic prosperity forced manufacturers to make major reductions in manufacturing costs. There was no room for theorizing. Manufacturers, regardless of their industry or the condition of their business, planned cost reductions using every conceivable means. In particular, the need to establish effective just-in-time (JIT) production systems, which supply "only the necessary things, at the necessary times, in the necessary amounts," increased even more. Of course, opinions are regularly voiced pointing out the negative aspects of the JIT method, such as traffic jams due to more frequent deliveries and the problems caused subcontractors by shifting more functions to them. However, the era when markets could absorb products beyond what customers need—products produced because of "big plan" production and "big plan" delivery—has ended. Among production activities, even though there are differences in degree, one essential condition for preventing increases in production costs is to produce "only the necessary things, at the necessary times, in the necessary amounts." JIT production, which started in the auto industry, is gradually spreading to all types of industries and across all manufacturing processes. This increasing adoption of JIT and the frequent product changeovers required, has made the improvement of setup operations indispensable. The era of mass production using Ford-style production systems has passed. In contrast, production of a variety of products in small lots has increasingly become the norm. Techniques for efficient small-lot production have grown in importance across all types of industry.

SETUP TIME REDUCTION AT MANUFACTURING SITES

Definition of Setup

The *setup* operation is to change the manufacturing conditions from those for producing a certain product to those for producing a different product, including *stopping the present job and preparing the conditions for start of the next job.* Except for cases where one specific product is produced in a dedicated line, it is periodically necessary to change the product produced on the line from product A to product B. In this context, *setup time* can be defined as follows: from the stop of production of product A until the start of production of nondefective units of product B.

Here, it is important to note that setup time does not refer to only the time for changing molds or other tooling and parts, but rather to the entire time from stopping production of the previous product until the production of nondefective units of the next product has been confirmed. In this context, *single setup* means that setup time has been reduced to a single-digit number of minutes—less than 10 minutes. However, it means only the time when equipment is stopped for setup (so-called internal setup time) and does not include the time for incidental operations related to setup (external setup) that occur before and after equipment stoppage.

The Necessity of Techniques for Setup Time Reduction

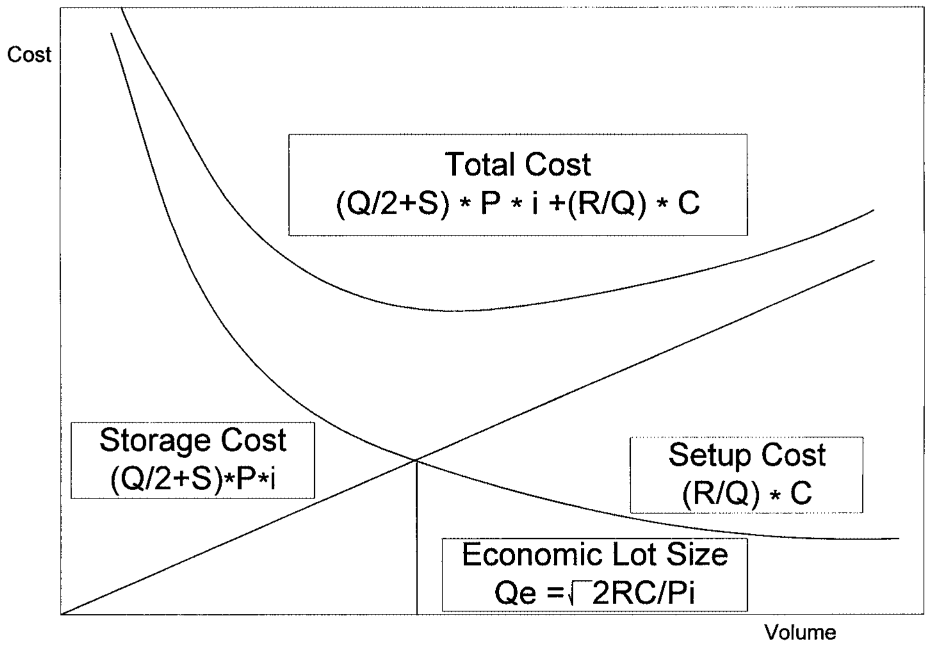
The operation of changing over the product being produced—the setup operation—will occur for any line not dedicated to a specific product. Thus, thinking generally, setup time will be required, and if a variety of products are produced in small lots, the equipment utilization ratio should fall to that extent, and the amount of operating time available should decrease. In this context, one might expect that there is one optimum production quantity that would result in an economic balance between the equipment utilization ration and the quantity produced in a lot. This is the concept of an *economic lot size,* which considers setup cost in a mass production situation. This concept of economic lot size is similar to that of economic order quantity and can be found by the following formula:

$$Qe = \sqrt{2\ RC/Pi} \tag{1}$$

where Qe = economic lot size
R = estimated amount of demand during scheduling period
C = setup cost
P = purchasing unit price
i = inventory cost factor

Additional cost formulas are show in Fig. 4.4.1.

However, at the time the general formula was applied in mass production situations and became established as common sense, the late Shigeo Shingo of Japan proposed a way of thinking that totally overturned that common sense. His innovative concept focused on separating internal and external setup. According to this concept, when the setup time and cost are large enough, the formula for economic lot size can be applied, but when those factors are relatively small, an economic lot size does not really exist, and lots can be made as small as desired. Based on this new thinking, Shingo developed an original production technique that later became the foundation on which the late Taiichi Ohno built the Toyota production sys-



C: Cost of one setup
i: Inventory cost factor
P: Purchase price (per unit)
R: Estimated amount of demand during schedule period
Q: Quantity (lot size)
Qe: Economic lot size
S: Minimum stock level

FIGURE 4.4.1 Mass production and economic lot size.

tem as a production system for small-volume production of a variety of products and for cell type "one piece flow."

Advancement and Development of Setup Improvement Techniques

With the broad adoption of the Toyota production system, the technique of single setup, which had initially been used with industrial press equipment, was gradually applied to all kinds of equipment that use molds, such as injection molding, forging, and casting equipment. It spread from the auto industry to every other industry including consumer electronics and home appliances, semiconductors, heavy electrical, construction, sales and distribution, food service, and the like. Furthermore, Shingo selected this name, *single setup,* to indicate a high level of achievement, comparing the reduction of setup time to a single digit (i.e., less than 10 minutes) to a single-digit golf handicap. Activity in the field of setup improvement, which became famous through the popularity of single setup, has continued to make progress. Recently, research in this area has progressed to the stage that one-cycle setup and zero setup have even been achieved.

The concept of setup improvement, which really got its start from the innovative idea of "considering internal setup and external setup separately," gained attention not only from Japan's leading manufacturers but also from companies around the world, and in just a short time it became widely accepted. It was systematized as the single setup technique and was fully presented in the book, *A Basic Orientation for Achieving Single Setup,* by its developer, *Shigeo Shingo* [1].

Technically, production activity may be thought of as a matrix of process steps and tasks or operations. It is important to recognize that work can be accomplished while separating the progression of process functions (forming, changing the material, assembling, breaking down) from human operations (setup, main operations, spare time) as depicted in Fig. 4.4.2. In other words, if preparation tasks and follow-up tasks (i.e., the setup operation) can be done in a way that does not hamper the progress of the production process and can be completed while equipment is actually operating, the amount of time lost to stoppages of product production or to equipment downtime can be remarkably reduced. If this separation is made, the setup tasks for which the equipment must absolutely be stopped are actually very few. This results in a significant reduction of internal setup and further breakthroughs become possible.

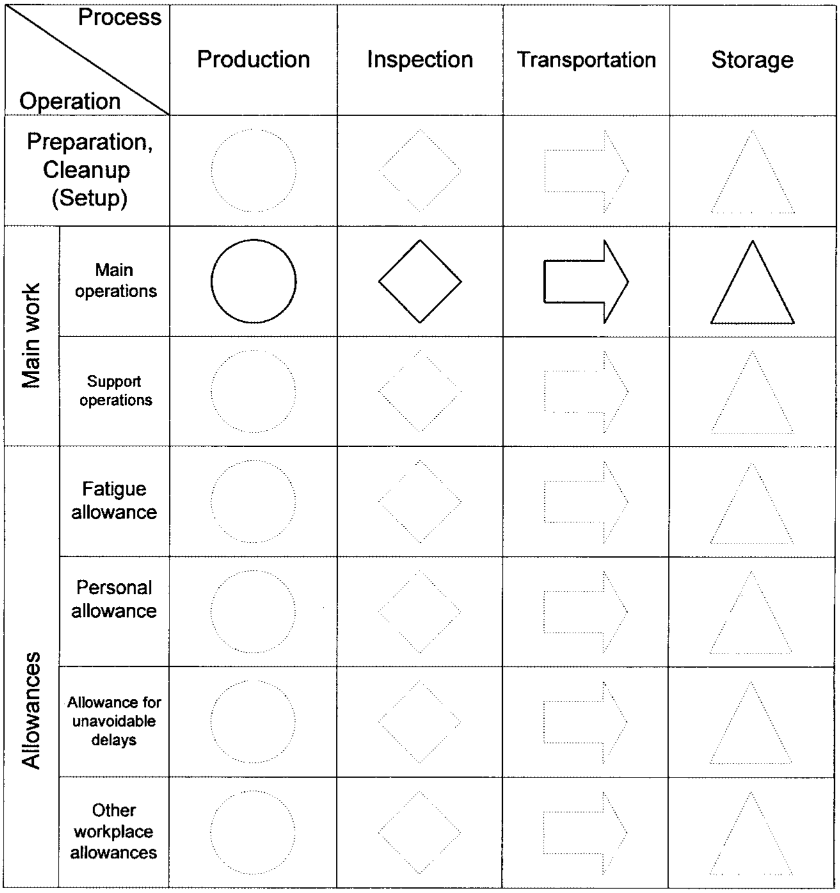

Process
Operation
Production
Inspection
Transportation
Storage
Preparation, Cleanup (Setup)
Main work
Main operations
Support operations
Allowances
Fatigue allowance
Personal allowance
Allowance for unavoidable delays
Other workplace allowances

FIGURE 4.4.2 Matrix structure by process and operation. (*From* A Basic Orientation for Achieving Single Setup *[1].*)

Although there are differences in degree, if engineers assigned to setup improvement accept the challenge of single setup, they will be able to experience a logical progression for achieving setup improvement. That is, in dealing with this subject, engineers progress through the following process steps or levels, achieving greater and greater amounts of setup time reduction:

- Abolishing unnecessary operations
- Converting internal setup activities to external setup
- Shortening the essential internal setup operations—standardizing molds and connectors (including functional standardization), controlling adjustments, converting the final lock-in step to a one-touch clamping
- Reducing external setup

The details of each level will be described in the next section but we can identify categories related to the amount of time reduction achieved. Those can be ranked as follows:

- *Single setup:* The setup operation is completed in less than 10 minutes (within 9 minutes, 59 seconds).
- *Momentary setup:* The setup operation is completed in less than 1 minute.
- *One-cycle setup:* The setup operation is accomplished during one cycle of production (stoppage time is equal to one cycle).
- *Setup under one cycle:* The setup operation is completed almost instantly so that production is stopped for less than one product cycle.
- *Zero setup:* Changeover to another product can be completed without any setup tasks.

Notes: (1) Setup time is sometimes defined as solely the time needed for mold changeover, not including the time until product flow is restored—which is incorrect. Setup time must extend until confirmation of the flow of nondefective products has resumed. (2) Cycle time = total order running time/order quantity (i.e., the time for production of one product unit).

Basic Procedures for Setup Time Reduction

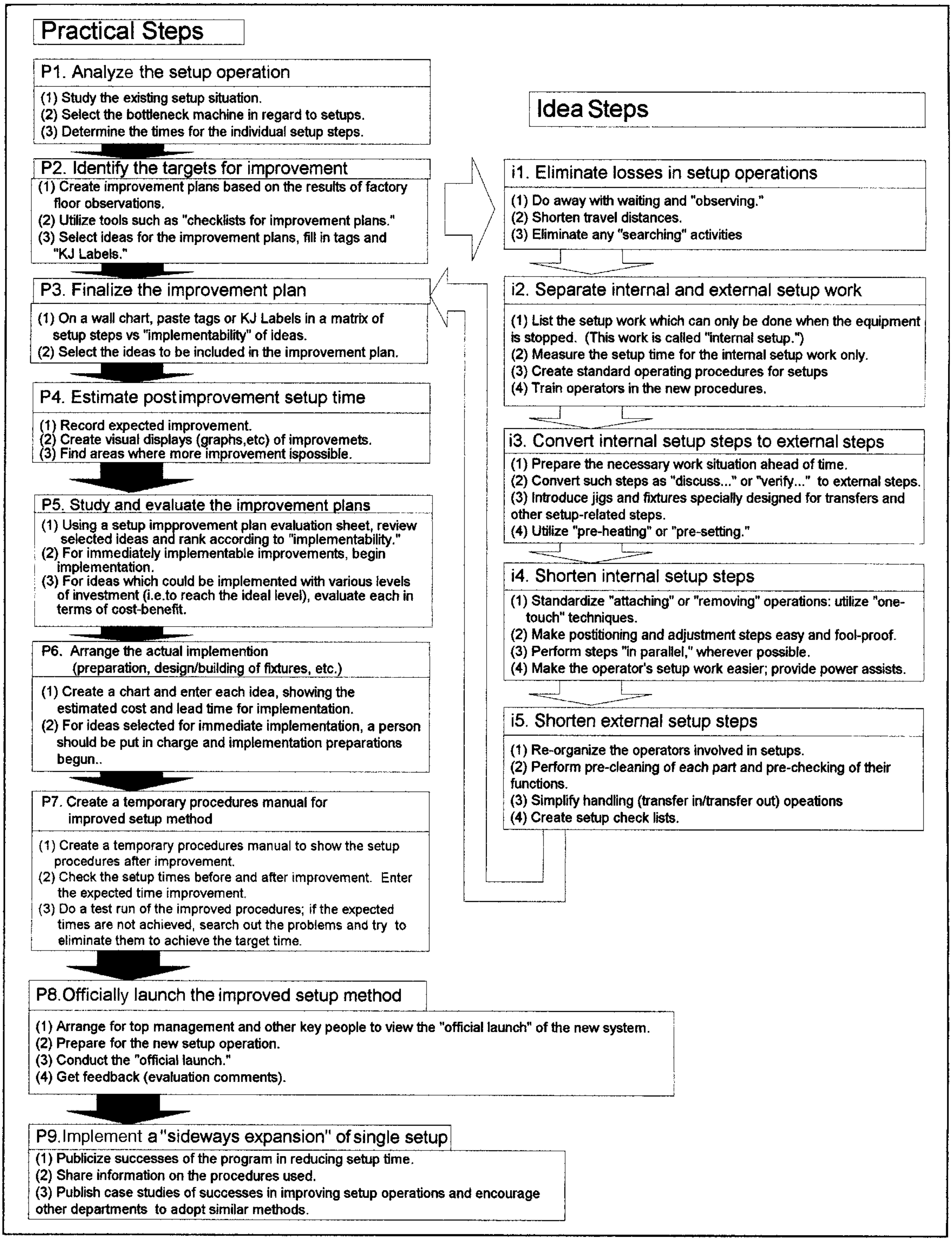
Basic procedures for setup time reduction, which can be viewed as the basic steps to single setup, are outlined in Fig. 4.4.3. The following sections briefly describe these basic procedures in sequence:

Practical Step 1: Analyze the Setup Operation. Often the importance of a setup operation is not recognized, or if recognized, technical difficulties are encountered and improvement efforts are abandoned. For such reasons, in cases where the existing setup operation takes more than a few hours, it frequently happens that no one has clearly understood what tasks are being done, and in what order. There may be some differences depending on the equipment used or the way operations are performed but the typical time schedule for all tasks in the setup operation, prior to improvement, can generally be summarized by the following breakdown [1].

1. Preparation and cleanup of materials, cutting tools, jigs, and fixtures, and checking their functionality—30 percent
2. Installation and removal of cutting and similar tools—5 percent
3. Centering and setting of dimensions and other parameters—15 percent
4. Trial run, adjustments—50 percent

To begin, relinquish the negative attitude that further reduction of setup time is impossible and do not express excuses like "The setup operations at our factory are special," or "Our experienced staff has thoroughly dealt with this issue and has improved the situation as much as possible." It is necessary to start again with a fresh mind and analyze the setups carefully.

In practice, the first question to be asked is which setup operation, from among those performed on various factory equipment, should be selected as the model and carefully observed



Practical Steps

P1. Analyze the setup operation
(1) Study the existing setup situation.
(2) Select the bottleneck machine in regard to setups.
(3) Determine the times for the individual setup steps.

P2. Identify the targets for improvement
(1) Create improvement plans based on the results of factory floor observations.
(2) Utilize tools such as "checklists for improvement plans."
(3) Select ideas for the improvement plans, fill in tags and "KJ Labels."

P3. Finalize the improvement plan
(1) On a wall chart, paste tags or KJ Labels in a matrix of setup steps vs "implementability" of ideas.
(2) Select the ideas to be included in the improvement plan.

P4. Estimate postimprovement setup time
(1) Record expected improvement.
(2) Create visual displays (graphs,etc) of improvemets.
(3) Find areas where more improvement ispossible.

P5. Study and evaluate the improvement plans
(1) Using a setup impprovement plan evaluation sheet, review selected ideas and rank according to "implementability."
(2) For immediately implementable improvements, begin implementation.
(3) For ideas which could be implemented with various levels of investment (i.e.to reach the ideal level), evaluate each in terms of cost-benefit.

P6. Arrange the actual implemention (preparation, design/building of fixtures, etc.)
(1) Create a chart and enter each idea, showing the estimated cost and lead time for implementation.
(2) For ideas selected for immediate implementation, a person should be put in charge and implementation preparations begun..

P7. Create a temporary procedures manual for improved setup method
(1) Create a temporary procedures manual to show the setup procedures after improvement.
(2) Check the setup times before and after improvement. Enter the expected time improvement.
(3) Do a test run of the improved procedures; if the expected times are not achieved, search out the problems and try to eliminate them to achieve the target time.

P8. Officially launch the improved setup method
(1) Arrange for top management and other key people to view the "official launch" of the new system.
(2) Prepare for the new setup operation.
(3) Conduct the "official launch."
(4) Get feedback (evaluation comments).

P9. Implement a "sideways expansion" of single setup
(1) Publicize successes of the program in reducing setup time.
(2) Share information on the procedures used.
(3) Publish case studies of successes in improving setup operations and encourage other departments to adopt similar methods.

Idea Steps

i1. Eliminate losses in setup operations
(1) Do away with waiting and "observing."
(2) Shorten travel distances.
(3) Eliminate any "searching" activities

i2. Separate internal and external setup work
(1) List the setup work which can only be done when the equipment is stopped. (This work is called "internal setup.")
(2) Measure the setup time for the internal setup work only.
(3) Create standard operating procedures for setups
(4) Train operators in the new procedures.

i3. Convert internal setup steps to external steps
(1) Prepare the necessary work situation ahead of time.
(2) Convert such steps as "discuss..." or "verify..." to external steps.
(3) Introduce jigs and fixtures specially designed for transfers and other setup-related steps.
(4) Utilize "pre-heating" or "pre-setting."

i4. Shorten internal setup steps
(1) Standardize "attaching" or "removing" operations: utilize "one-touch" techniques.
(2) Make postitioning and adjustment steps easy and fool-proof.
(3) Perform steps "in parallel," wherever possible.
(4) Make the operator's setup work easier; provide power assists.

i5. Shorten external setup steps
(1) Re-organize the operators involved in setups.
(2) Perform pre-cleaning of each part and pre-checking of their functions.
(3) Simplify handling (transfer in/transfer out) opeations
(4) Create setup check lists.

FIGURE 4.4.3 Basic steps for implementing single setup.

and measured. To do this, (1) a survey of each setup operation is made and (2) the bottleneck equipment in terms of setup time is identified and selected. Next, the basic written materials related to the selected setup operation (layout drawing of the area surrounding the equipment, equipment operation manuals, setup procedure manual, etc.) are gathered. Then, using a VTR (video tape recorder), (3) a time study of the setup operation is conducted. Recently, VTRs that display and record time (in units of seconds) are becoming widely available, making it remarkably easy to record the elapsed time for each task in the operation. In addition, some stopwatches are capable of storing "lap times" in memory, making it possible to record the times for short task units very efficiently. However, even if such analytical instruments are available, it is unnecessary to analyze in units of seconds an operation that takes five to six hours. It is important to choose the appropriate level of analytic accuracy according to the characteristics of the operation being analyzed. Figure 4.4.4 shows a completed (filled out) form for a setup analysis.

Practical Step 2: Identify the Targets for Improvement. The second practical step to focus on is the potential for improvement. First, referring to the times measured in Practical Step 1 for each task based on the observations on the factory floor, improvement-oriented questions should be asked: "Why must this task be done?" or "Why cannot this task be made part of external setup?" Here, it may be helpful to use an improvement idea checklist or some of the many reference materials that are available. In *A Basic Orientation for Achieving Single Setup,* the most effective methods for developing improvement ideas in this step are organized and presented as *idea steps.* These idea steps can be roughly organized into five classes. Generating ideas need not follow a system, but a systematic process for idea generation may be very effective when working to reduce setup time. It enables those involved to keep organized in their minds which idea at what idea step is being considered at any moment, and in that way energy can be focused where the priorities lie. The subsequent sections summarize the five idea steps. After following these steps, ideas should be organized on paper tags or KJ labels (labels used in the KJ method conceived by *Jiro Kawakita*).

Setup Analysis Sheet		Changeover A→B		Date of Analysis Done by: /
No	Work Content	Elapsed time	Task time	Improvement ideas
1	Preparation work		-	
	1) Open safety door.	↓	-	
	2) Put tool carrier beside the equipment.	10 s	10 s	Introduce specially designed jigs and fixtures.
2	Preparation of setup			
	1) Go to operator panel and turn SELECT	12 s	2 s	Move select switch to a closer position.
	switch to "manual".			
	2) Set out and position oil pans (two).	17 s	5 s	Use specialized covers to eliminate need for oil pans.
	3) Take out the finished goods and put them on	21 s	4 s	Complete removal of finished products prior to setup.
	loader oil pan.			
3	Loosening operations for machining center			
	1) Take off upper cover.	30 s	9 s	Make it one-touch or abolish.
	2) Get perforating tool and unprocessed parts.	43 s	13 s	Place tools and parts close at start, as part of external setup.
	3) Load unprocessed parts and reposition center.		-	
	4) Push FULLSTOP button.	56 s	13 s	Convert dock adjustment to one-touch operation.

FIGURE 4.4.4 Example of a setup analysis form.

Idea Step 1: Eliminate Losses in Setup Operations. Meaningless tasks within the setup operation are often done simply by habit, without a clear purpose. Thus, the first idea step is to pursue the function of each task, asking why that task is performed. If any tasks are found that have no particular meaning or are simply a waste of time, they should immediately be eliminated from the setup operation.

Idea Step 2: Separate Internal and External Setup Work. Next, it is necessary to identify those setup tasks that can be done only if the equipment is stopped (internal setup) and separate them from tasks that can be done without stopping the equipment (external setup.) Without this distinction, all setup tasks may be treated like internal setup tasks and the equipment may be stopped much longer than is necessary. In this step the rule that "equipment may be stopped for setup only if the specific setup task cannot be done without stopping the equipment" is enforced. Many tasks can be accomplished without having to stop the equipment, including preparation of cutting tools, molds, jigs, and fixtures, and certain follow-up tasks. Thus, simply by differentiating between internal and external setup, setup time requiring equipment stoppage can be reduced by 30 to 50 percent.

Idea Step 3: Convert Internal Setup Steps to External Steps. In this step setup tasks that currently must be done while the equipment is stopped are changed and improved so that they can be done while the equipment is in operation. For example, a tool-centering operation had been done with the equipment stopped, but it was found that presetting could be done with the equipment operating. Likewise, another procedure required that the equipment be stopped after setup until the quality of newly produced products could be verified. However, by increasing the reproducibility of manufacturing conditions for nondefective products, it was possible to restart the equipment immediately (without a trial run) with full expectation of obtaining quality products. In this way, it is often possible through creative thinking to change setup tasks presently done as internal setup to external setup.

Idea Step 4: Shorten Internal Setup Steps. At this point, the internal setup tasks still remaining must be thoroughly analyzed and improved. It is important to approach this effort motivated by a strong determination that "We will achieve single setup (setup time less than 10 minutes) in any way possible!" Those individuals involved, based on examples of past successes, must change their viewpoints and way of thinking in the effort to contribute innovative ideas.

Idea Step 5: Shorten External Setup Steps. At present, the equipment operator must in many cases do setups along with his or her regular tasks, and it is becoming less common for someone other than the operator (a supervisor for example) to take care of external setup tasks. Therefore, total improvement of the setup operation generally cannot be achieved without significant reduction of external setup tasks as well. To accomplish this, it is necessary to look closely at all the things which change as part of the setup operation and seek to eliminate or reduce them.

In following these idea steps, it is not necessary that each one be used in the course of a single time study. After the improvement ideas have been organized, selected, and implemented, one can return to an idea step that could not be used in the first round and come up with improvement ideas in that category, which can then be implemented. Improvement through this kind of a repetitive process is very effective.

After one round of Idea Steps—from (i1) to (i5), return to Practical Steps. Practical Step 3 is next in the procedure sequence.

Practical Step 3: Finalize the Improvement Plan. After a multitude of improvement ideas have been submitted for each task in the setup operation, the relevant ideas should be assigned to one of four levels: (1) easy to implement, (2) requires a small investment, (3) requires a medium investment, or (4) is too idealistic. (The latter category is for ideas that are good, but which probably cannot be implemented at a reasonable cost or in a reasonable time frame.) Here, the Post-it brand tags or KJ labels that were filled in as part of Practical Step 2 are used, and it may be convenient to mount them on a large sheet of paper hung on a wall. Next, mark with a large black dot the tags with improvement ideas that are candidates for adoption. It is important to address as many tasks of the setup operation as possible and adopt as many ideas as possible.

Practical Step 4: Estimate Postimprovement Setup Time. On a time improvement analysis sheet, for each task in the setup operation, calculate and display the total reduction in time that will be possible through the adopted improvement idea. Then for each setup task, this time reduction is subtracted from the current time (as observed and measured in the time study), and an estimate of the time for the setup operation after improvement is calculated. Then a graph is made showing the observed time value, total improvement time (reduction in time), and the forecasted time value following the improvement. If there are setup tasks whose time values are still large even after improvement, more improvement ideas must be generated and further reductions attempted.

Practical Step 5: Study and Evaluate the Improvement Plans. Using a setup improvement–idea evaluation form, the ideas that were classified into the four levels described in Practical Step 3 are reviewed and the determination as to whether each idea will be adopted is made and recorded. Preparations should be started immediately for ideas assigned to the "easy to implement" level. In some cases an idea from the "requires a small investment" or "requires a medium investment" level will have been given a high priority for adoption. If it duplicates (solves the same problem) as an easy to implement idea, then no preparatory work should be done on the latter idea because it would shortly be replaced anyway. Each of the improvement ideas classified at the levels of small investment, medium investment, or idealistic is evaluated as to whether it should be adopted. In conducting this evaluation, the required investment should not be the only criterion, but rather the expected effect and the cost performance of the idea should be considered. Moreover, since the initially estimated investment cost is only a tentative number, it may be possible, with a little creativity or innovation, to come up with a much less expensive solution that will produce the same effect. For this reason, improvement ideas should not be rejected only because the investment cost may be large.

Practical Step 6: Arrange the Actual Implementation. For each improvement idea adopted in Practical Step 5, a request must be made for the required hardware changes. To facilitate this, a form is generally used that outlines the arrangements needed for rebuilding the hardware to achieve the planned improvement and contains realistic estimates of the expected cost of the improvement idea and the required time. For each adopted idea, a person must be placed in charge and preparations for implementation are then begun.

Practical Step 7: Create a Temporary Procedures Manual for the Improved Setup Method. Once the hardware changes have been made on a test basis according to the improvement idea and the effectiveness of the improvement verified, a tentative procedures manual for the improved setup operation is developed. In addition to outlining revised operating procedures, the temporary procedures manual for the setup operation lists the estimated time for each setup task. In this way the total setup time before and after improvement can be verified. If, at this late stage, it is found that the time improvement is small, it may be worth going back to earlier steps and seeking further improvement ideas.

Practical Step 8: Officially Launch the Improved Setup Method. To recognize the efforts of everyone involved, it is desirable to launch the new, improved setup operation with "fanfare," inviting upper management and key people from outside the company. Such an opening ceremony, enables everyone to see the results of the improvement, and also sends a strong message as to the importance of ongoing setup improvement activity. Announcing the "grand opening" date well in advance has the advantage of also providing a stimulus for the people engaged in setup improvement to complete their work on time and this may unleash a level of effort not usually seen! In addition, putting improvement activities in the limelight can provide a big impetus to further activity of this type.

Practical Step 9: Implement a "Sideways Expansion" of Single Setup. If single setup is achieved in one part of the factory, it is beneficial to publicize the achievement and recognize the good results. Moreover, the accomplishments should not be allowed to end there, but similar improvements should be immediately applied to similar processes and equipment throughout the factory. This "sideways expansion" of the adopted improvement ideas might occur by applying them just as they are to the other lines or equipment that were examined in Practical Step 1 during selection of the model line for improvement. For other types of equipment, the setup improvement methodology can be applied to seek similar benefits.

Considering the results of a setup improvement activity, simply reducing setup time for one piece of equipment will not have that large an impact because only the labor-hours needed for setup have been reduced. Besides, if setup operation tasks have merely been changed to external setup tasks, the total labor-hours will not have been reduced at all. Therefore, when a single setup has been successfully achieved, it is essential to think in terms of sideways expansion so that single setups can be achieved throughout the entire line producing the product, and other lines as well. If the improvement process described previously is viewed as a progression of setup time reductions, it will appear as shown in Fig. 4.4.5. This can be easily understood as a process of gradually "digging deeper," through use of the idea steps, while repeating the practical steps. That is, while repeating the practical steps over and over, the idea steps (differentiation of internal setup and external setup, changing internal to external, improving internal tasks, and shortening internal and external times) are gradually applied more intensely. Of course, since these are idea steps, in practice it is quite acceptable to develop ideas that span these four steps.

Applying Time Reduction Techniques to Production Control

As mentioned in Practical Step 9, if a reduction of setup time is limited to one piece of equipment, the economic benefit is not large. In order to obtain a large economic effect, sideways expansion must be achieved across all equipment groups producing a certain product family, including both front-end and back-end equipment. (Since equipment groups usually take the form of a production line, in the following discussion we will refer to an *equipment line.*) We call this *achieving single setup for line changeover.* Similarly, the sideways expansion must apply to all the product types produced on the line. Even if there is just one product type for which single setup cannot be done, then every time the line is setup, either to start that product or return to making it, extra effort is required, and the efficiency of the whole line decreases.

When single setup has been thoroughly adopted for all products and across all equipment lines, the concept of economic lot size must be reconsidered. In a case where previously the rule was production lot size = 1000 units, production can be divided into smaller lots, where, for example, processing lot size = 100 units. In such cases, if all the equipment throughout the line is synchronized and converted to one-piece flow, the lot production time can be reduced to $\frac{1}{10}$. In this case, the number of setups increases by 10. However, if the setup operation, which previously took 2 hours is reduced to 3 minutes (i.e., single setup has been achieved), setup time will be 10 times 3 minutes or a total of 30 minutes, which is still 1 hour 30 minutes less than the previous setup time. Accordingly, the production period can be shortened drastically without a large drop in equipment utilization. If this production period is reduced to $\frac{1}{10}$, inventory other than safety stock can also be reduced to about $\frac{1}{10}$, and the total capital turnover rate (= sales ÷ total capital) can be greatly improved, and a definite improvement in financial results can be clearly shown.

A program called ESCORT (Equivalent & Synchronized Production Control Technique), which offers a synchronized, uniform lot-size production system would be appropriate to use in this context. Once a certain level is set for synchronization and uniform lot size, the program simulates factory setup time and indicates for each line to what level setup time must be reduced and by what percentage equipment utilization must be increased, for example,

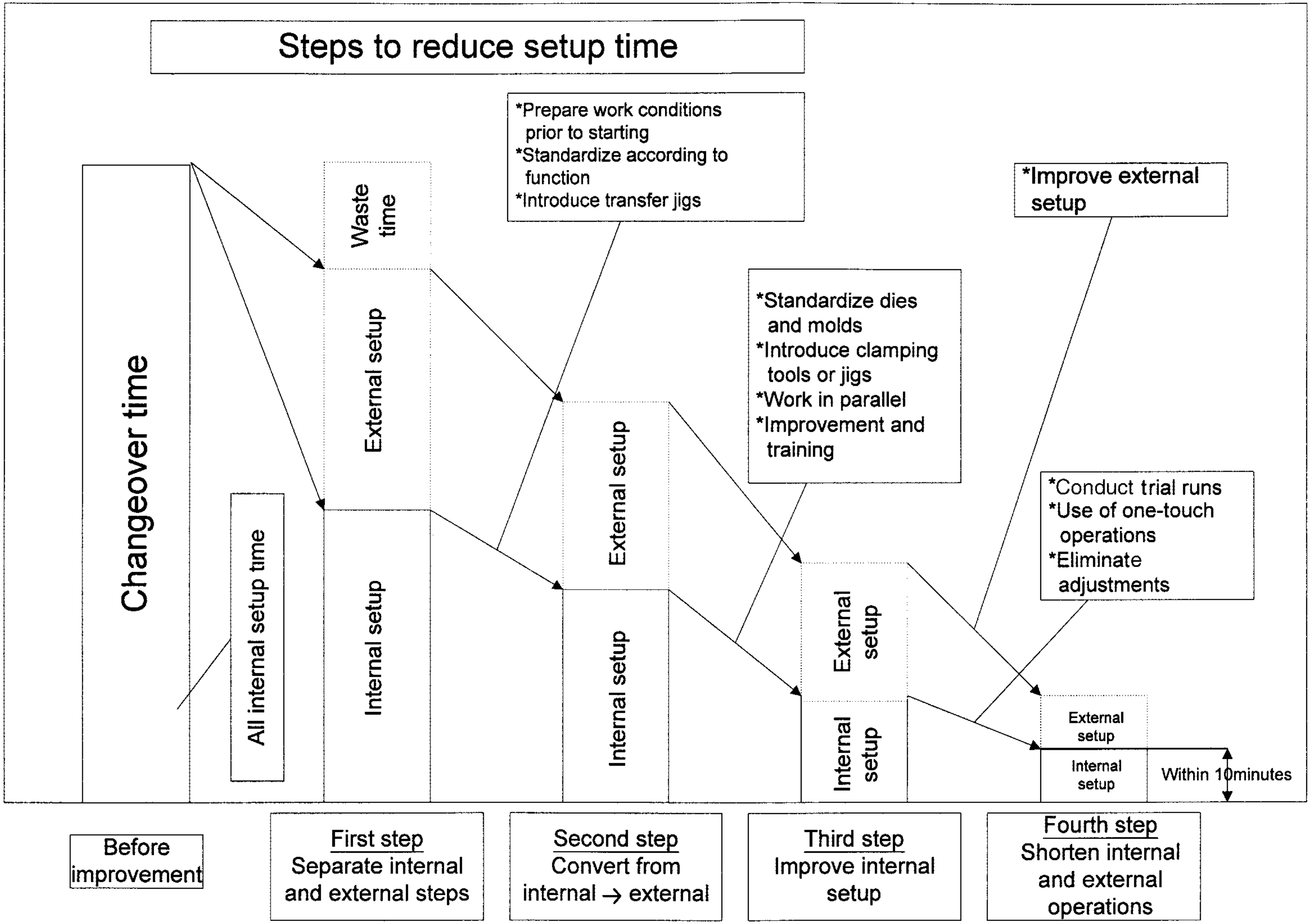

Steps to reduce setup time
*Prepare work conditions prior to starting
*Standardize according to function
*Introduce transfer jigs
*Standardize dies and molds
*Introduce clamping tools or jigs
*Work in parallel
*Improvement and training
*Improve external setup
*Conduct trial runs
*Use of one-touch operations
*Eliminate adjustments
Changeover time
All internal setup time
Waste time
External setup
Internal setup
External setup
Internal setup
External setup
Internal setup
External setup
Internal setup
Within 10minutes
Before improvement
First step
Separate internal and external steps
Second step
Convert from internal → external
Third step
Improve internal setup
Fourth step
Shorten internal and external operations

FIGURE 4.4.5 Improvement process for setup time reduction.

through elimination of equipment breakdowns and minor stoppages. It thus indicates targets for factory improvement and provides a strong motivating force as well. In other words, the program provides a framework for setup improvement to be done based on a clear recognition of needs and targets. As for production control, fundamental factory improvements such as setup improvement or reduction of equipment breakdowns can only produce major results if they are implemented along with improvements to the production control system. The following list summarizes the benefits of setup improvement [1]:

1. Nonstock production (inventory minimization) becomes possible.
2. Equipment utilization factors increase, resulting in greater production capacity.
3. Setup mistakes are eliminated and trial runs become unnecessary, resulting in fewer defective products.
4. Production conditions can be fully set ahead of time, improving product quality.
5. Simpler setup results in safer work.
6. Through standardization, fewer jigs and fixtures are required, and organization/arrangement of work area is improved.
7. The total setup operation, including both internal and external setup, is reduced, enabling a reduction in required labor.
8. Once changeovers can be done in less time, they become less troublesome; resistance to them is reduced.
9. Simplified changeovers can be done by any operator: people with special skills are not required.
10. Production lead time can be dramatically reduced.
11. Quick response to changes in demand is enabled; the flexibility and responsiveness of manufacturing are greatly increased.
12. Blind spots in management's thinking (about improvement potential) can be eliminated.
13. A radical improvement in thinking is achieved, making what was previously considered impossible, possible.
14. Major advances in manufacturing methods become possible.

Generalization of the Setup Improvement Procedure

Basic Concepts of Setup Improvement. Single setup improvement has a big impact on the people concerned. The know-how gained from setup improvement should be applied to achieving single setup for all sorts of equipment in all types of companies. Also, the know-how gained from this activity should be generalized so that for equipment, molds, jigs, fixtures, and tools, the objective of reducing setup time (i.e., single setup) can be taken into account even as early as in the design process. Careful consideration must also be given to information about the weak points of the equipment as it is actually used. The objective is to use this information to design equipment that has a higher level of reliability, maintainability, safety, and flexibility. This approach is called MP (maintenance prevention) design. In regard to setup considerations, when using MP design, one should pay particular attention to achieving a high level of flexibility. The general techniques used in MP design are itemized here:

- *The technique of standard connections.* Even though the individual parts for a setup may vary the elements that connect them are standardized:

  Tool chucks.

  Attachment of robot hands.

  Piping couplings and/or wiring connectors.

- *Fixed/variable design techniques.* This is a design method that, in cases of multiple models of each product, divides the design into fixed parts that cannot be varied, and changeable parts that can be varied with each product model. The method also seeks to maximize the fixed aspects of the design. This approach may also be applied to setup, maximizing the use of fixed components, fixtures, and so on, which do not have to be changed during a product changeover. In the cases where changes are essential, they are limited to only those absolutely required to accommodate the shape of the product:

  Parts (tool) change by quick insertion.

  Minimizing the number of changes required.
- *The technique of organizing job parts.* With this technique, for all jobs, the required parts are fixed as a set:

  Outline templates are used to fix the "home positions" of tools and parts so they are easy to find.

  Operators are given special "setup belts" equipped with the necessary tools.
- *The search index technique.* Layout is organized so that required parts can be readily found. Location numbering is used, specifying:

  Cabinet number.

  Shelf number.

  Location number.
- *Technique of potential theory.* Create a layout and procedures so that objects can be moved easily and walking distance is reduced:

  Convert mold and die handling to "air float."

  Maintain critical open spaces.

  Apply preheating.

The Setup Activity Index. The *setup activity index* is an indicator of the easiness of beginning the next job. This index measures the extent to which the changeover of a line can be done quickly and with minimal activity; the more activity needed, the higher the score and the worse the situation.

In concrete terms, points are allocated as follows:

When changing from production of one product to production of a different one, no tooling changes are required anywhere on the line	0 points (setup time: 0 seconds)
Automatic changeover by pushing a button	1 point (setup time 0–1 seconds)
One touch to remove previous tooling and install the next	2 points (setup time 1–3 seconds)
Positioning with an alignment fixture	3 points (setup time 1–3 seconds
Tightening bolts is required	20 points (setup time 2–3 minutes)
Test production is required	50 points (setup time 2–3 minutes)

These points are tallied for every task in the setup operation, and the smaller the point total, the better the setup/changeover situation. Of course, the changeover situation (good or bad) could simply be measured in terms of a time value, without going to the trouble of an index system. However, such an index can also be useful when designing equipment that will require setup activities. For example, in cases where alternative design approaches are being considered, the index number can be used as an evaluation standard, enabling the ease of setup to be evaluated while the equipment is still on the drawing board.

SETUP TIME REDUCTION IN ADMINISTRATIVE AND SUPPORT DEPARTMENTS

An Improvement Technique for Applying JIT to Support Business Activities

Based on an understanding of the "matrix structure of production, considering process steps and operations," as shown in Fig. 4.4.2, when the function of process steps is broadly interpreted, the concept of shortening setup time can even be applied to supportive business activities. In other words, if the process function of certain supportive business is to decide and implement, it can be understood that there will be preparatory or collateral functions required for accomplishing the process function, which are equivalent to the setup operation in the production area. However, support business has the characteristics that (1) the business process is hard to understand based simply on observations, (2) specific business activities tend to be assigned to specific individuals, (3) output is not fixed, (4) assigned tasks vary according to the abilities of the individual, and (5) business performance is difficult to measure. For these reasons, in practice, it is hard to specify what must be done, and to what extent, as a setup operation for a certain support activity. Also, in many cases, examining the importance of tasks is not done properly. As a fundamental issue, it would be worthwhile to apply standardization techniques and single setup to support business activities, even though they are harder to analyze than direct productive activities. In this context, we will introduce an approach to breaking down support business activities into their main business tasks. This in turn makes it easier to apply *kaizen* improvement activities and single setup techniques to these support activities.

Applying Single Setup to General Support Activities. As the main setup operations in the support (or indirect) business field, fundamental business activities (which occur regardless of the type of company or the job title) are discussed with the intention of improving them.

Single Access of Office Supplies. In regard to supplies such as writing instruments, paste, scissors, and paper cutters, by exercising thorough control "accessing office supplies in a single (digit) time unit" (here, the time unit would be seconds, so a single-digit time unit would be less than 10 seconds) can be achieved by

- Sharing items and using outline marking to show the home position for each item
- Guaranteeing the return of borrowed items through a thorough program of designated storage places for all articles
- Clearly indicating the name of the borrower on the "in use" tag
- Preventing out-of-stock situations through double-bin systems and order-point control
- Controlling total inventory quantities through the display of upper and lower limits

Single Cleaning of Office Equipment. Through the following activities, single-time (in this case less than 10 minutes) cleaning is realized, and at the same time, beautification of the workplace environment is achieved:

- Remove all side tables.
- Remove cabinet doors.
- Share individual desks and change to circular tables.
- Put casters on all equipment to avoid fixing them to the floor; this reduces cleaning time.

Accessing Business Papers in 30 Seconds. In a surprisingly large number of workplaces, employees struggle to locate and retrieve documents. This can be avoided through the following activities, and realization of accessing documents in 30 seconds can be achieved. When it is still impossible to access documents that quickly, the problem probably lies in the system for classifying documents, in the actual storage rules themselves, or in the manner in which the rules are followed. In such cases the filing system must be totally reviewed.

- Remove unnecessary documentation.
- Store routine documentation in a separate place.
- Thoroughly implement a system for clearly identifying documentation with title, tracking or serial number, and day/month/year of creation.
- Guarantee the ability to retrieve documents by clearly writing on each binder (using a label, etc.) the storage location, devising storage arrangements that prevent binders from falling over, and, for borrowed binders, displaying the name of the person who has borrowed it.
- Create a document systematization scheme for all documents in possession by a group as well as for those documents not in a group's possession but still frequently used by them. Also ensure that all involved members are aware of, and conform to, the system.

Among these documents, documentation recorded in electronic media formats is of course included. A good barometer of whether a workplace has achieved a good system for common access to documents is whether electronic media documents can be accessed in less than 30 seconds.

Telephone Response. In many cases, a company's telephone system is its representative, its window to the outside world. A telephone system that does not cause distress or wasted time and is relevant to the application and comfortable to use can bring great benefits to the company. In this regard, a useful exercise is to call in to the company's telephone system from the outside and rate its effectiveness according to the following criteria. For any areas where the response of the telephone system was inadequate, changes (retraining, etc.) should be done to correct the problems.

Example: An outside person calls your department, but the person they wish to speak with is out.

- Did someone answer the phone in less than three rings? (Or if after the third ring, did they apologize for keeping the caller waiting?)
- Did the person who took the call announce the company (or department) name and his or her name?
- Did the person write down the key information? Who from what company called and whom did they wish to speak with and about what?
- If the message was complicated, did the person repeat it, and have the caller confirm it?
- Did the person give a simple word of appreciation and explain that they will convey the message?

There are many variations to receiving phone calls, such as forwarding or dealing with an upset caller, but it is necessary to train employees to be polite in all cases and handle calls in an appropriate professional manner.

Visitor Reception. Any employee may have the opportunity to receive a visitor. In order to receive visitors pleasantly and adequately according to the special circumstances of each visit, employees must be trained in methods for dealing with various kinds of visitor situations.

- If the visitor was looking for something, did the employee take the initiative to ask which department the visitor was looking for?
- Did the employee ask the visitor for the necessary information (i.e., their name and company name, with whom they wished to meet, and about what)?
- Once the employee has understood the nature of the visitor's business, he or she should escort the visitor to the appropriate department or tell them how to find it.
- The employee should confirm that the visitor has understood the instructions and can follow them.

The way of dealing with a visitor may vary according to the company's situation and where the visitor is met, but it is desirable to train employees in every part of the company, using appropriate hypothetical example situations and asking employees to act out what they would do.

Improvement of Business Flow. Next, turning to the business flow, improvement is necessary through reducing to a minimum staff-hours and other costs associated with each business activity, based on a clear understanding of the volume and flow of each business activity in the company.

Improvement of the business flow is accomplished by following these steps (see Fig. 4.4.6):

Create Business Task Table. The purpose of this overview is to clarify what kind of activities occur in the subject business center and who handles these tasks by taking how many staff-hours. When the scale of business is large, break it down into the three classes of large items, medium items, and small items, and when the scale is small, break it down to just two classes: large items and small items. In the latter case, an item classified as "small" would be an activity of 5 to 20 staff-hours.

Select Business Area as a Model for Improvement. After the business overview chart is completed, based on the importance of each of its "small items" and their broad usage in other businesses, a "test case" is selected which will become the object of initial improvement activities. However, for the first such project, it will be easier if a business which is relatively simple and independent from other business is selected.

Chart the Existing Business Flow. After selecting a model business, diagram the flow of work, posting the currently used business forms based on the flow of work, and clarify the details of the conduct of business by actually talking to the person in charge.

Identify Problems and Develop Improvement Plan. The business as currently conducted is then studied and the problems for each task, or *business activity* are identified. Next, improvement ideas are considered. These must solve the problems, while enabling the business to be done without additional staff-hours. It will be easier to come up with improvement ideas if one takes a hard look at "what the final output of the model business is" and considers "what processing of input information should be done to get that final output." Reasons may be given for the current procedures, but it is necessary to confirm the validity of such reasons. There is no need, however, to be bound by the way things are presently done. In addition, one should not merely consider improving each business activity in isolation, but should look at improvements that cut across several business activities.

Outline Business Flow After Improvement. After examining the improvement ideas for each of the business activities, the most promising of those should be adopted. Then an overall postimprovement business flow should be created. Here, it will be easier to understand the implications of adopting each improvement idea if the ideas are classified according to degree of difficulty of implementation: (1) can be readily implemented, (2) requires small investment, (3) requires medium-sized investment, and (4) the ideal solution (which may be very hard to implement.) Setting procedures for postimprovement business flow is equivalent to creating the temporary procedures manual introduced in relation to equipment setup improvement. The new procedures need to be organized and displayed in a way that makes it easy for the people in charge of the business to see the improved business flow. For example, the forms to be used after improvement should be designed and actual samples posted in their proper places on the flowchart.

Estimate Benefits of Improvement Plan and Implement. For each adopted improvement idea, one needs to provide estimates not only of the direct costs required for adoption but also of the indirect costs, such as the staff-hours of effort and the time period needed for implementation. Total cost is then compared to the expected benefits.

Provide Training for Improvement Plan and Confirm Results. Based on the adopted improvement ideas, the postimprovement business must be clearly imagined and explanations and training offered in parallel with implementation. Also, after introduction of all improvement ideas and after employees get thoroughly accustomed to the new business procedures, a time study (of various processing times) is done to confirm the improvement effect.

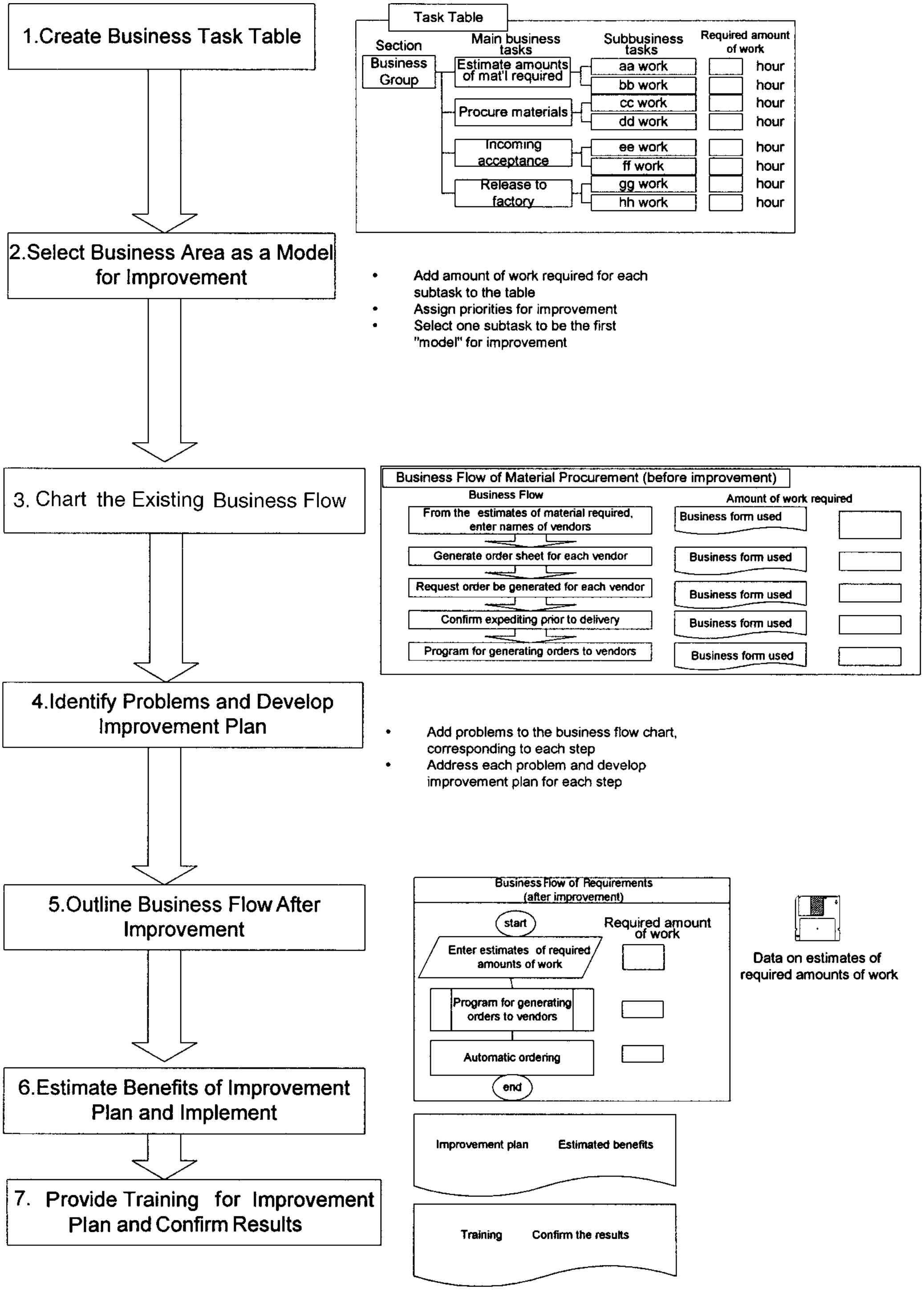

1.Create Business Task Table
2.Select Business Area as a Model for Improvement
3. Chart the Existing Business Flow
4.Identify Problems and Develop Improvement Plan
5.Outline Business Flow After Improvement
6.Estimate Benefits of Improvement Plan and Implement
7. Provide Training for Improvement Plan and Confirm Results
Task Table
Section
Main business tasks
Subbusiness tasks
Required amount of work
Business Group
Estimate amounts of mat'l required
Procure materials
Incoming acceptance
Release to factory
aa work
bb work
cc work
dd work
ee work
ff work
gg work
hh work
hour
hour
hour
hour
hour
hour
hour
hour
Add amount of work required for each subtask to the table
Assign priorities for improvement
Select one subtask to be the first "model" for improvement
Business Flow of Material Procurement (before improvement)
Business Flow
Amount of work required
From the estimates of material required, enter names of vendors
Generate order sheet for each vendor
Request order be generated for each vendor
Confirm expediting prior to delivery
Program for generating orders to vendors
Business form used
Business form used
Business form used
Business form used
Business form used
Add problems to the business flow chart, corresponding to each step
Address each problem and develop improvement plan for each step
Business Flow of Requirements (after improvement)
start
Required amount of work
Enter estimates of required amounts of work
Program for generating orders to vendors
Automatic ordering
end
Data on estimates of required amounts of work
Improvement plan
Estimated benefits
Training
Confirm the results

FIGURE 4.4.6 Procedure for a business flow improvement project.

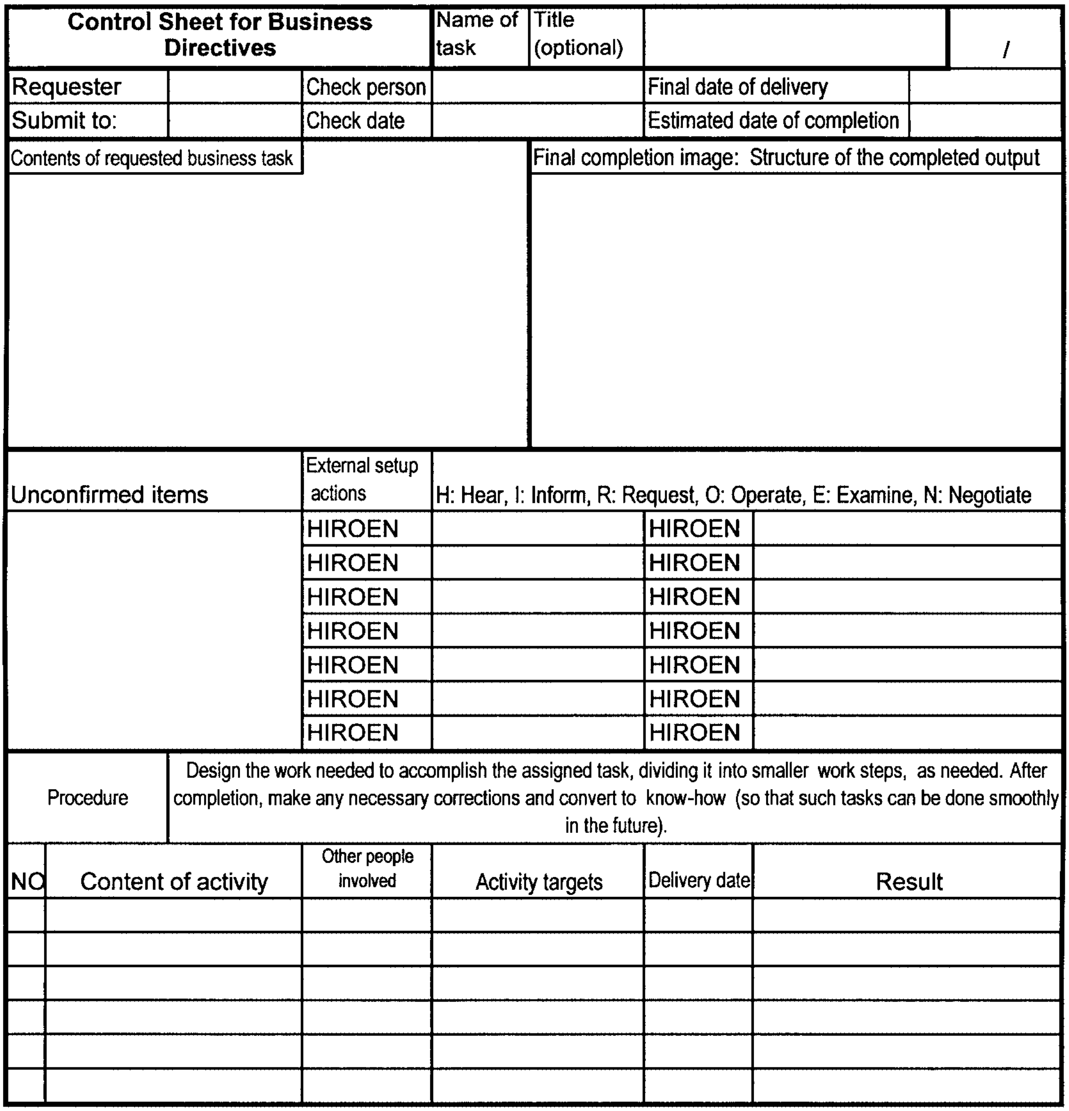
As for sideways expansion following the model case, this should be done in the order of priority, according to the expected room for improvement of each business area. This was described in Practical Step 9 for setup time reduction.

If processing business flow information prior to inputting it into a computer is considered a setup operation, then support business itself can be regarded as a type of setup. If so, support business can be improved by using the same approach that was applied to the improvement of equipment setups. However, support business is not a simple business that can merely be given to computers for processing. Within the support business there are routine tasks that are essentially set business activities that are repeated, and nonroutine tasks of low repetitiveness. If we recognize that "improvement of routine tasks involves improvement of the processing method," while "improvement of nonroutine tasks involves improvement of the rules and systems for handling the task," both can be thought of as equivalent to preparatory tasks in a manufacturing situation. In that case, techniques from the manufacturing field can be applied to improve them. However, among nonroutine tasks, there are business activities that have very little repetitive content and cannot be carried out without human thinking or evaluation. In cases when a person is essentially doing the processing, the approach to improvement can be similar to process improvement in the manufacturing area—that is, applying basic principles such as conversion of the business activity to an assembly line structure, application of management principles, and control techniques.

Improving Management of the Giving/Receiving of Business Directives. Certain types of waste and losses, which are uncommon in direct operations, are frequently seen in support business. For example, in Japan, under the name of education and training, it seems that waste has become rather common. This originates from unclear business direction from superiors, and it is typical of the inefficiencies found in nonroutine tasks. To eliminate such waste, a form such as that shown in Fig. 4.4.7 can be used effectively to avoid confusion both in giving instructions and in receiving/understanding them. In addition, the effectiveness of this tool is enhanced if the records are kept to serve as a guide or manual the next time a similar business situation occurs.

This form is called the control sheet for managing the giving and receiving of business directives. It was devised to enable the efficient handling of nonroutine business directives (tasks) from superiors in one's department or other departments in the organization. Immediately upon receiving such a task, the employee should look through past (filled out) sheets to check whether such a task has been received before. If no previous sheet with a similar task is found, a new sheet should be filled out indicating the originator of the directive, the person who checked or authorized it, the deadline for completion, and so forth. The column entitled "Contents of the requested business task" is carefully filled in to ensure that the contents of the request (exactly what task is to be done) are accurately understood. Furthermore, it is important from the beginning to visualize what kind of form the final response must take to satisfy the original requester. This will be entered in the column designated "Final completion image." Any information related to accomplishing the task should be entered in the column designated "unconfirmed items" ahead of time, to avoid the risk of failure at the end. Boxes indicate items that must be checked off when completed. If there are issues requiring interaction with other parties, either before starting the task or while accomplishing it, those should also be listed. The nature of the interaction may be indicated by a circled letter in the column, "External setup actions": H for Hear, I for Inform (information), R for Request, O for Operate, E for Examine, or N for Negotiate. A detailed explanation is then entered in the right-hand column. Finally, the sheet is completed by designing the optimum business procedures for carrying out the requested task and entering them onto the sheet. In practice, if it is possible immediately after receiving a directive to contact the party that issued it and confirm their expectations, it will be much easier to do the task in a way that will satisfy them. Even if the form is not filled out in exact detail, it will still serve as a personal record and can be quite effective just in that role. Where possible, a procedure can be used whereby the requester fills out the form beforehand.

Improving the Management of Working Time. In support business, personal schedules are difficult to follow. Losses in this area cannot be overlooked. Even if individuals schedule their



Control Sheet for Business Directives	Name of task	Title (optional)		/

Requester		Check person		Final date of delivery	
Submit to:		Check date		Estimated date of completion	

Contents of requested business task	Final completion image: Structure of the completed output

Unconfirmed items	External setup actions	H: Hear, I: Inform, R: Request, O: Operate, E: Examine, N: Negotiate		
	HIROEN		HIROEN	
	HIROEN		HIROEN	
	HIROEN		HIROEN	
	HIROEN		HIROEN	
	HIROEN		HIROEN	
	HIROEN		HIROEN	
	HIROEN		HIROEN	

Procedure	Design the work needed to accomplish the assigned task, dividing it into smaller work steps, as needed. After completion, make any necessary corrections and convert to know-how (so that such tasks can be done smoothly in the future).

NO	Content of activity	Other people involved	Activity targets	Delivery date	Result

FIGURE 4.4.7 Control sheet for managing the giving / receiving of business directives.

activities themselves, setting aside time for joint activities with other staff, such as meetings, often these schedules are seriously disrupted by interference—contacts with superiors, phone calls, and so on. To improve this situation, uniform rules for time use can be adopted. For example, working time for each day can be divided into three categories: (1) time for intradepartment communication, (2) time for individual work, and (3) time for communication through meetings. Efficient time use is achieved by strict adherence to this routine. An example of working time allocation is shown in Fig. 4.4.8.

Communication time will be filled with activities such as checking on communicated matters or transfer of work from one employee to another. No meetings are held. Individual time is set aside for individuals to fully concentrate on their tasks. Time for meetings and commu-

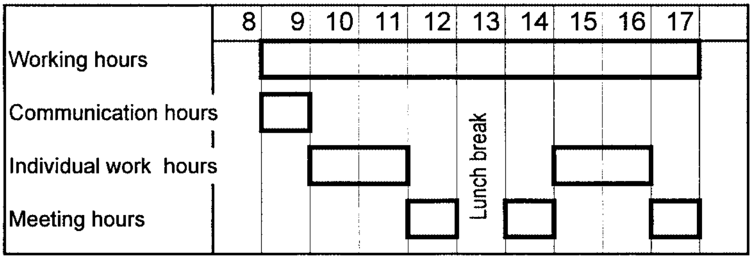


FIGURE 4.4.8 Time schedule showing allocation of time.

nication is used for interdepartmental meetings and communication within each work area. By establishing these time slots and having all employees, as much as possible, schedule activities of the designated type into them, employees can concentrate on the planned activity, without interruption, and make good progress.

Single Support Setup for Single Decision Making and Single Action Taking

In the field of manufacturing, the technique for reducing the time for setup and follow-up operations related to actual processing functions is called *setup time reduction.* This same way of thinking can also be applied to administrative and support business activities. In the manufacturing area, process functions (such as fabrication) can be thought of as those that directly add value to a product in terms of directly advancing its progress toward completion. These include functions such as forming, making changes to material, or assembling. In contrast, are functions that do not directly add value. These include the preparatory or follow-up activities that we have lumped together under the term, *setup.* This approach of classifying functions as direct, value-adding or non-value-adding can be applied to administrative/support business also. Since such business does not consist of direct, value-adding functions (like forming or assembling), it is equivalent to what, in the manufacturing environment, we have called setup. In one sense, it must be admitted that even in administrative/support business, some functions such as evaluation and implementation are process functions (value-adding functions), but almost all other support operations may be regarded as (non-value-adding) setup operations. In a previous section, we described a typical technique for improving business functions by first viewing them as setup operations. What do such improvement techniques seek to achieve? Similar to improving setup in the manufacturing setting, the objective of these techniques is to "raise the potential so that it is possible to do the next work." In other words, using JIT terminology, it is to supply only the necessary things (in this case, usually information), at the necessary times, in the necessary amounts to support the evaluation and implementation function. This can be called *setup improvement* of the administrative/support business, or achievement of *single support setup* to enable quick decision making and rapid action taking. To coin a new term, we might call this *single support setup for single decision/single action.* Indeed this approach is a fruitful avenue for improvement, once its importance is recognized.

SETUP TIME REDUCTION IN THE MANAGEMENT FIELD

Rapid Management

Thus far, we have seen how the basic concept of setup improvement can be applied not only in the manufacturing area but also in the field of administrative/support business. We suggest that the same thinking can be applied across all the management activities in a company as well. It may be difficult to draw a clear line separating management from the administrative/support field, but what is clearly different is that in management, the process function is the decision-making function with the purpose of making management judgments to maximize profits. Preparation of the necessary information for this purpose can be regarded as setup in the management context.

"The company offers products the market needs, charges prices for them as compensation, and makes a profit." This is a considerably simplified company model, but the key point for successful business is repeating this cycle quickly and achieving a satisfactory profit margin. In other words, it is essential to understand the trends as to "what the customer considers good, what the customer considers not good, what the customer has trouble with, and what the customer wants to buy." Then, in response to these trends, management must decide what the company is going to supply and what actions it will take. The faster and more timely this process can be done, the better, and the cheaper the prices of the solutions supplied and the higher the "hit ratio" for the company's products. This is true for manufacturing (whether custom, make-to-order manufacturing, or mass production) and for the service industry, as well.

Of course, controlling the internal climate, or culture, of the company is another management responsibility. This includes such things as ensuring that all employees understand the corporate vision and are taking actions in concert with it, and that they are not selecting inefficient means to an end or taking actions that are at odds with customer needs.

"The company offers (as promptly as possible) products the market needs, charges prices for them as compensation, and makes a profit." Timely repetition of this cycle is called *rapid management.* An image of how rapid management is achieved is shown in Fig. 4.4.9.

In Japan, the company that best achieves this image of rapid management is Kao, which produces and sells cosmetics and toiletry products. Kao is famous for its SIS (strategic information system), which consists of the following six component systems:

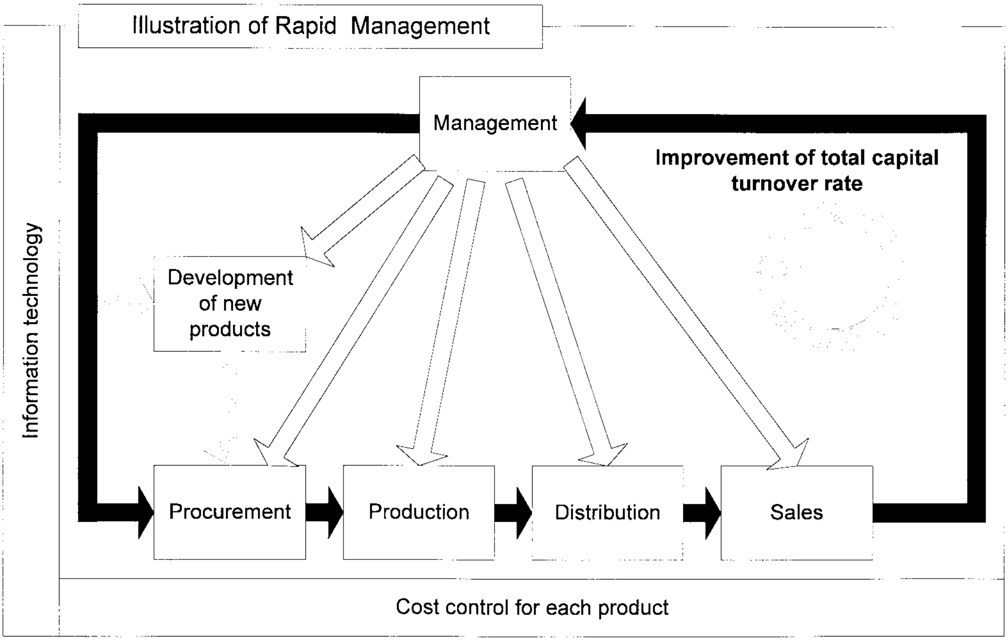


Illustration of Rapid Management
Information technology
Management
Improvement of total capital turnover rate
Development of new products
Procurement
Production
Distribution
Sales
Cost control for each product

FIGURE 4.4.9 Illustration of a system for rapid management.

1. *Echo system:* This system seeks to use customer information from complaints and inquiries to improve product development and customer service.
2. *Market intelligence system* (*MIS*): This system gathers information from cooperating supermarkets on market trends (including information on the POS [point of sale] marketing activities of competitors) and makes use of it for correcting production plans and strengthening the company's marketing power.
3. *Distribution information system* (*RJS*): As one part of a program supporting retail stores, Kao actually assumes the business activity of receiving and issuing orders on behalf of the stores and through this, information on competitors is obtained.
4. *Commute to the retailer system:* Because each salesperson (whether from a branch office or a distributor) is given the task of receiving and issuing orders from the information terminals of the retailers, the salesperson need not continually return to the company's office or other base in the area. This system supports both the retail store and the salesperson.
5. *Logistics information system* (*LIS*): The LIS system enables the distribution center to give shipping instructions to the most suitable factory (in terms of efficiency, logistics, etc.) among all the factories in the country and to deliver products to retail shops via the most cost-effective route. This system synthesizes new order information, shipping information, distribution route information to achieve numerous benefits such as reduction in inventory, speedier deliveries, and reduction in physical distribution cost.
6. *Computer-integrated manufacturing* (*CIM*): By enabling two-way flow of sales information and production information between factories (domestic and foreign) and the sales division, the overall result is that the system operates as though all the factories were one factory.

What should be clear from this actual case is that it is possible to achieve the desirable situation shown in Fig. 4.4.9, wherein "the information which is the raw material for decision-making is always readily available in a usable form to enable optimal performance of process functions such as new product development, procurement, production, physical distribution, and sales" [1]. In other words, in the management field, setup improvement amounts to providing the information that will be the basis for quick and effective management judgments in a condition in which it can be readily utilized for decisions that result in profit improvement.

Importance of Adequate Information Provision and Quick Decision Making

In regard to techniques for making setup easier, it is necessary to consider where such efforts should be applied to obtain greatest effect. Probably the best target for their application is the watch tower at the front lines of the competitive battlefield. Where is the serious fighting going on? What kind of information will enable the company to beat its competitor? It is important to focus on the place where the most intensive fighting is occurring. In addition, it is critical to deliver information to the place where it can be put to use, and to do so with such timing that its effective use is enabled. Systems that catch pertinent information (changes in the wind on the battlefield—i.e., the market) and relay this information to headquarters promptly can be of great importance in determining who wins the contest.

In addition, valuable information is useful only if it is delivered to the most appropriate party. Therefore, it is essential to deliver important information to the person having decision-making authority. In the ideal situation, the person in that position will have superior skills enabling him or her to make effective use of the information, but if not, a capable support person should be properly positioned as an aide. The keys then to effective use of information: It must be in a ready-to-use form and it must reach the right person in the right department—the one who can put it to use, and that person must be capable of doing so.

In what we have called *rapid management,* what is important is the swiftness of management decision making and action. This of course includes swiftness in getting the necessary information, but it also includes the quickness in moving from decision to action, and the quickness in achieving necessary structural improvements. In regard to the latter, the capability to respond to changes is the most important strength and requires flexibility in thinking. This type of quickness influences a company's performance and is reflected in its key indexes, such as return on capital. Things that managers can change are the product, the manufacturing and sales systems, and the company organization. While constantly monitoring the allocation of these three management resources, it is important to respond to changes in the climate in which the company operates, and always to try to convert external changes into opportunities.

CONCLUSION

We have investigated techniques related to improvement of setup and have discussed the application of these techniques beyond their conventional use in manufacturing to other fields such as administrative and support business as well as to the management field. We attempted a broader application of the concept of process as reflected in "the process/operation network structure of manufacturing" referred to by Shigeo Shingo. There may be objections to our definition of evaluation and implementation as the process function for the administrative, support, and management fields. However, by organizing our thinking in this way, all other activities could be thought of as preparatory operations. This approach enabled us to highlight an important distinction that was consistent and useful. It seemed a wasteful use of such an important concept as single set up, and the techniques it provides for enhanced productivity, to limit its application only to the manufacturing field. After applying the single setup concept, as a new benchmark to other fields, we expect the interest in and understanding of this valuable tool to increase.

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BIOGRAPHY

Shinya Shirahama is a chief consultant with Tokyo-based JMA Consultants, Inc. (JMAC.) He received a bachelor's degree from the National Nagaoka University in 1982, and completed graduate studies there in 1984. He joined JMAC the same year and achieved the rank of chief consultant in 1991. He has worked extensively with various departments of major Japanese automobile makers, especially in the areas of setup time reduction and maximum utilization of equipment. During half-year projects, he has frequently helped clients reduce setup time by two-thirds or more. He is often called on for teaching/training assignments in Japan, China, and Korea, dealing with such subjects as Total Productive Maintenance, Factory Automation Project Leadership, and equipment design. On the "idea side" of business, he consults in such areas as unleashing employee creativity and stimulating new thinking in the workplace.

CHAPTER 4.5

CASE STUDY: ACHIEVING QUICK MACHINE SETUPS

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Manufacturing organizations have rigorously sought to improve machine uptime productivity. As product lot sizes are reduced to lower costs and to accomplish just-in-time (JIT) production, the ratio of setup time to available production time increases. There is a significant savings potential in reducing setup times. The methodology and the organization of the workplace determine the effectiveness and timeliness of setup times. This case study reviews the techniques used and the results achieved in reducing setup times by employee teams.

BACKGROUND AND SITUATION ANALYSIS

As production labor and equipment costs increased, it was critical to improve productivity by minimizing indirect costs. One of the largest components of indirect labor was setup time between lot runs. Using industrial engineering tools and employee teams, the setup portion was to be reduced by 50 percent with minimal capital or expense costs.

Accomplishing the setup process in a timely and efficient manner was referred to as a *quick setup.* In manufacturing, achieving quick setups provided at least two specific scenarios:

1. Total setup time decreased which facilitated more available production time. There was an increase in operating capacity and a reduction in capital investment requirements. The main advantage was the reduction in the number of machines required to meet production requirements. Downtime as a percentage of available time was reduced.

2. A constant number of hours was invested in setting up between production runs; as the average setup time decreased, lot run sizes were decreased accordingly. This facilitated smaller lot runs which were desirable for JIT manufacturing. Advantages included a reduced work-in-progress (WIP) inventory level and a reduced finished goods inventory requirement. Both of these level reductions were possible due to the increased reactiveness by production to customer requirements.

From an industrial engineering perspective, setup time was fraught with cost savings potential. Many of the tools and techniques used to improve productivity in direct labor operations were used to improve set up responsibilities.

In this case, indirect labor attributed to setting up machinery was from 25 to 35 percent of total labor cost. Two different types of production functions were chosen as test cases for quick setup potential.

One of the production lines counted and packaged components which were packed into the finished carton. The other production lines consisted of multiple machines and parts handling mechanisms which processed component parts. All of these production teams consisted of four or five employees per shift and each line operated three shifts per day. Each work center was experiencing between 45 to 90 minutes per setup with an average of one occurrence per shift; there was a total of 28 work centers of these processes.

If this transitional time between lot runs was reduced by 50 percent without deceasing lot run sizes, there would be a $1,100,000 annual labor savings. The first step for an improvement effort was to get management's attention; cost savings numbers of this magnitude got their attention.

In order to achieve synergism between teams and to maintain enthusiasm for improved setups, an industrial engineer was chosen as the facilitator for all teams. An industrial engineer had the technical expertise and the organizational skills necessary to facilitate quick setup teams. In past setup improvement efforts at this company, untrained facilitators did not achieve any noticeable or lasting results.

At the beginning of the training, production requirements were restricted and additional capacity was needed. The lot sizes were to remain constant as the available production time was allocated for increased capacity.

Since this case involved multiple plant locations, it was critical to address the issue of management support. Both corporate and plant management's understanding and support for quick setup methodology were necessary. Several organizational meetings with plant and corporate management personnel were conducted for the purpose of gaining their support. The entire training program and company objectives were reviewed. There was widespread acceptance and support for a quick setup initiative.

In summary, this company used equipment for producing different products for different customers and different market segments. Hence, they changed over equipment from producing one part to producing another part; setup time was not recognized as being value-adding and needed to be minimized by using many of the industrial engineering tools which were used to improve productivity of direct labor operations. This case study will show how those applicable industrial engineering activities were used to achieve quick machine setups.

OBJECTIVES AND SCOPE

Before an effort was initiated to reduce indirect costs attributed to setup, it was crucial to define the objective and to establish the scope of the effort. Employee teams were to undertake reducing setup time by 50 percent. The established objective was stated as follows: "The objective is to improve setup methods and organization of work-to-be-done; teams are not to issue work orders for maintenance or engineering."

Management decided that quick setups were to be achieved by the use of employee teams. These teams were to consist of the employees directly responsible for operating the equipment. The perceived advantages of using these teams included the following:

During the analysis, a team developed more ideas, provided different viewpoints, built on each other's ideas, and got more work done.

During setup implementation, a team had a sense of ownership and team spirit, had influence with management, and had influence with other workers. "None of us is as smart as all of us."

By focusing on what the teams did for themselves, they were not dependent on the priorities of other departments.

The essence of this last statement was to prevent "buck passing." It was easy to write work orders for others to solve the team's problems. Maintenance and engineering functions did not need the additional workload that would be generated by these teams. So, each team was challenged to do what the members collectively could do for themselves to reduce setup time.

The scope of their activity was focused on their own work center and on issues that they could solve with minimal support from other departments. They were encouraged to discuss issues and procedures with other departments but were not to delegate work to these other departments. With approval of all three shifts, teams were encouraged to implement those improvements costing less than $250.

Each team was able to focus on and to accomplish significant reduction in setup times. During their work sessions, team members interacted and shared new ideas, which led to better methods and organization. Even though some teams worked in different plant locations, their solutions and recommendations were often similar.

ORGANIZATION OF THE PROJECT

Successful team projects required extensive planning effort. With the objectives and scope clarified, the next step was to select teams and to share the purpose of the setup activity and training. It was critical to explain the ramifications of reducing the setup time to each team and to insure their continued employment as setup times were reduced. The effort to select the teams and to begin the training process proved key to achieving the goals and objectives. Most team members accepted that improving their efficiency of operation would make the company more responsive to customer needs and more competitive. Having completed the team selection process, the orientation and the training phases began.

The success of setup reduction began with targeting the initial processes and teams. Since two processes were limiting capacity and were causing shipment constraints, they were chosen as the initial training areas. An industrial engineer was chosen to facilitate the training and implementation effort.

The industrial engineer worked with production personnel to qualify the teams that were most likely to succeed. Production management began the process by listing each team to be considered and discussing the merits that each team offered. Their objective was to identify those operational teams that accepted change and undertook challenges. The evaluation included reviewing all employees assigned to the equipment. After reviewing team candidates and recommendations from first-line supervision, the facilitating industrial engineer approved the ones to undergo training.

The selected team candidates were contacted by their first-line supervisors to review the training proposal. In these discussions, each employee was introduced to the planned quick setup training and any questions were answered. If all employees operating the work center agreed to accept the challenge of improving their operation and to undertake the training, their team became a part of the training process. After all of the teams were screened and the final list of four teams was complete, the training began.

Training consisted of two phases. The first phase consisted of two sessions which were the orientation sessions for all team members. The industrial engineer coordinated the agenda and facilitated these meetings. The second phase was the hands-on training and implementation phase. These sessions consisted of weekly meetings, which spanned a 4 to 6 month period and were conducted during the operating shifts. Each team was allowed to progress at its own pace; no effort was made to keep the teams on the same time schedule. With the four teams operating on three shifts, there were twelve shift-meetings, each team meeting once each week for an hour. During these meetings, an elected team leader coordinated the meeting and the industrial engineer acted as facilitator.

To provide structure and organization to the weekly meetings, a training booklet was used. This booklet was developed by the industrial engineer in an effort to guide the team and to provide techniques to use in improving setups. This training aid consisted of two sections. In the first section, team members were introduced to setups and to the importance of reducing setup activity. In addition, the steps to use in the team process were detailed, and specific action points were explained. The second section consisted of an explanation of tools and techniques which the team might use in their project activity, such as action logs, analysis charts, check sheets, improvement plans, operator–machine charts, and videotaping.

The first section of the booklet was used during team meetings to guide the discussions. Team members took turns reading and discussing designated portions of the text. At each meeting, the industrial engineer determined what new material needed to be discussed at the next meeting; the team's leader was responsible for getting a volunteer to read that material ahead of time and to share the material at the next meeting. The technique of having the members lead the training sessions was very effective; presenters enjoyed sharing information from the text, and they often enhanced this material by adding knowledge gained from their own experiences.

In summary, organization of the project included addressing two processes that were limiting capacity and causing shipment constraints. The industrial engineer coordinated selecting the teams, getting buy-in from the selected participants, sharing the goals and objectives of achieving quick setups, and providing training aides for the process.

PROCEDURES AND APPLICATION OF TOOLS

In order to achieve quick setups, the procedure and application of tools were detailed in a training booklet given to each team member. The training began with the group orientation training, which included members from all of the teams and their immediate supervisors. The second phase of training was conducted through shift meetings. Each team went through the four steps of problem solving: (1) collecting data, which included defining the parts and volumes of parts processed and videotaping an actual setup; (2) analyzing data, which included reviewing the videotape to define each method step (each step was classified as internal or external and as to whether improvements were possible, and an analysis chart and a walking diagram were completed); (3) developing solutions, which included coming up with ideas to improve the present method and reduce walking activity; and (4) picking and justifying solutions, which involved selecting those techniques that would improve the setup time in a cost-effective manner. This whole process took between 4 and 6 months, the length of time depending on the team and on the manufacturing process involved.

Orientation Sessions

The orientation training sessions required the presence of team members from all shifts and their immediate supervisors. Each session lasted for two hours. This initial training was organized into specific time segments:

A. Sold the team members on management's commitment to quick machine setups.

B. Reviewed the need for quick setups. Each of the main reasons was explained and discussed in detail:

   1. Reducing the time to set up machinery saved money. When it took less time to change a machine from one lot run to another, it cost less to produce each part.
   2. Organizing the setup process made the job easier. Having setup tools and supplies available and ready to use eliminated the frustration of searching for needed items. Teams worked to simplify the setup process.
   3. By reducing setup time, more time was available to produce the product.
   4. If the number of setups per week remained constant, reducing the setup time resulted in higher productivity. That is, the amount of downtime decreased, resulting in an increase in the number of pieces produced per hour.

5. As a general rule, reducing setup time did not reduce people. Since the company was growing, additional employees were needed throughout the company.

C. Familiarized team members with quick setup terminology.

D. Convinced the team members that this training was valuable and needed.

Management commitment was key to getting the teams' attention. A videotape entitled *Achieving Quick Setups* was viewed early in the first orientation session. This company-made videotape featured a top company official explaining the quick setup concept; the facilitating industrial engineer provided the video outline and organized the material to be covered. During the dialogue, the company spokesman made a vivid comparison between an ordinary tire change on a car and changing a tire during a NASCAR or an Indy-500 pit stop. References of actual racing results due to the improved pit time were shared; several of the past few Indianapolis 500 races were won by the pit crews. Then, this tire change activity was related to setups between lot runs. The impact of speedy, effective tire changes was related to the importance of these crew members' working together to minimize the pit time. The discussion was directed toward industry and the need for reducing setup time to facilitate competion for worldwide business. The concept dialogue was concluded with emphasis on the benefits to the employee and to the company.

Since tire changing was perceived as a nonthreatening event—i.e., no one was being criticized personally—team members accepted the need for quick setups quite readily. This example was appropriate for the area and the employees involved in this case.

It was obvious that members were passively listening to the message presented on the *Achieving Quick Set-ups* video, and were not comprehending the intended message. A tactical change was incorporated quickly. Participants were given pencils and paper prior to the video's being shown and were asked to note particularly important issues mentioned in it. After viewing the tape, the group discussed the main issues and concepts involved. This training enhancement resulted in a better understanding of the reasons for changing the setup procedures.

This first orientation session was devoted to explaining and selling the importance of quick setups. This foundation was critical to overall team buy-in and affected team accomplishments. After a group discussion on management's commitment, the last portion of the session was devoted to understanding setup concepts and methodology.

Sharing the definitions of terms used during the training and implementation phases was important in this indoctrination phase. Keywords and phrases included the following:

Setup time—the total time it takes to convert *an individual machine,* measured from the last good part of the previous run until the first acceptable part of the next run. Setup time included (1) changing the machine by removing parts that were required by the previous product run, (2) installing parts onto the machine that are required by the new production run, (3) removing the completed parts from the previous run and bringing the material for the next production run to the machine, and (4) completing all of the machine adjustments required to achieve a quality part at the normal operating speed.

Changeover time—the same as setup time, except changeover relates to having *more than one machine* in a production line or at a work center.

External work—the work steps that can be performed while the machine is operating. This activity includes (1) bringing in new parts and positioning them in the appropriate location, (2) getting any tools, parts, and dies ready and in a position where they are easily accessible, and (3) getting needed tools from the tool room and having them at the machine ready to install.

Internal work—the work steps that require the machinery to be shut down or stopped.

After the teams thoroughly understood these terms, the first session was concluded.

During the second orientation session, which took place the following week, the training program was outlined and each step was summarized:

Collect data
Analyze data
Develop solutions
Pick and justify solutions

An overview of each step was covered and any questions were addressed. The supporting discussions strengthened the need for specific training, which was designed to assist the team in achieving quick setups. This session completed the combined shift meetings. The next phase involved each team's meeting during its normal shift time.

Each team was encouraged to anchor its meeting time to a shift change, lunch break, or shift break. This timing reduced the lost time going to and from meetings. The closest available meeting room to the work center was chosen; this room was quiet, and it was understood that interruptions were not permitted. Each shift team met once per week for one hour; each meeting was at a set time and on a specific day of the week, and cancellations occurred only if the majority of the members were not present. With the start of the individual shift meetings, members began to collect data.

Collect Data

Collecting data included reviewing the production data for the previous six-month period, defining the team's goals, and determining the products and volumes produced at their work center. Teams invited production-scheduling personnel to attend a meeting. Typical issues discussed included the product, specific parts, sizes, and quantities run on the equipment; characteristics of the setups; average lot sizes and whether lots sizes were decreasing; variables which made setup take less or more time; and setups which were repeated on a regular basis.

After reviewing this data, each team determined which attributes were key for tracking their production activity. Since setup reduction was not undertaken at the expense of product quality and production efficiency, goals for each of these parameters were determined. There were between four and six measurement points; too many measurements caused confusion. The weekly measurements for most teams included several statistics: good parts as a percentage of total parts produced (quality), good parts per hour on standard (productivity), downtime as a percentage of scheduled hours, average setup time, and number of setups. During this measurement selection and goal setting, the industrial engineer played a valuable role in guiding the team; selecting common measurement points for similar machinery and choosing attainable goals were key issues influenced by the industrial engineer. These goals were to be achieved during the next twelve-month period, and this time period included completing the quick setup training.

It was important to make the goals and the accomplishments visible; posting graphs at the work center accomplished this point. A bulletin board for these graphs mounted onto an appropriate machine panel, or on a nearby wall, was sufficient. A graph of each measured attribute showing the weekly averages of the measurement points for the past 6 to 9 months, plus enough room to post the weekly results of the next 3 to 4 months, was appropriate. The goal for each measurement was shown on the graph. As the data was provided to the team, a designated team member posted the weekly results onto each graph. Since our focus with the training was to have the team "do for themselves," the team recorded their own progress on the graphs. This approach reemphasized having the team provide their own service and not rely on others to do the work for them.

Charting of each team's progress was an important ingredient in making their efforts visible. Fellow employees viewed the results and made comments on the progress. In those locations where plant and corporate management periodically looked at the charts, the employees' acceptance was significantly higher, and the team's morale maintained a high level. In order to achieve maximum impact and results, management observed the charts and discussed the results with team members; this involvement resulted in more team commitment and interest.

Within the first 4 to 6 weeks of the initial shift meeting, the team videotaped a typical setup. Since videotapes were integral to the rest of the training, the time spent planning and carrying out the taping process was critical. Selecting the setup to video was crucial. The team agreed on which product setup was appropriate to represent an average, or a typical, setup.

Video cameras with the time stamp features were used; the recorded times were important in later analysis. Depending on the type of equipment and the equipment layout, videotaping was done differently to capture the events during the setup. In some cases, the work center was a small area, and the operator remained in a confined area. Operating the cameras from an overhead perspective was good for this application; industrial man-lifts were good tools to use in gaining the appropriate overhead perspective. In those cases where the operator's span-of-control was limited, the camera was placed on a tripod. When the activity was on a long production line, or the building had a low ceiling, or the operator covered a lot of distance during the setup process, following the operator around with a hand-held camera was appropriate.

Regardless of which technique was used during the taping process, the person being taped was in full view at all times. On the five-person production lines, a video camera was used to tape each team member; this meant there were five camera operators, each assigned to film one team member.

After selecting the appropriate camera arrangement, the team sought volunteer camera operators. Since the focus with the training was to have the team "do for themselves," the team used other employees to tape their setup activities; this approach reemphasized having the team provide their own service and not rely on others to do the work for them. In many cases, a team chose another setup team to operate the cameras. This choice had several advantages: these employees thoroughly understood why the video taping process was important, and they provided the highest quality of tapes.

If different employees were used for the taping process, an educational process was used. The camera operator was provided a sheet of directions, which included information on (1) how to operate the camera, (2) how to capture the work elements needed for the analysis phase, and (3) when to turn on and off the camera. Just prior to beginning the taping process, a team member provided an orientation session on the setup process and reviewed where the team members were working.

The taping began as the last few parts of the previous lot run were processed and continued until several acceptable parts were completed for the new lot run. The camera operator kept an overall viewpoint of the subject (a team member) being filmed and did not zoom in on the work being done. A minute method analysis perspective was not necessary since the person doing the job knew what was being done; the filmed team member provided the method steps and discussion during the analysis of the tapes.

Teams used these videotapes for self-analysis and were given the responsibility of keeping possession of the tapes for meetings. (Possession was an important credibility issue with the teams: a commitment was made to use the tapes for the team meetings only; any other use had to be approved by the team. After the teams completed their use of the tapes, the tapes were erased.)

The videotaping process was key to the entire training effort. As the videotaping process was being planned, it was important that the average setup be selected and that the team agree on the planned results. Thoroughly covering this issue before taping reduced validity problems later. In the early trials, a few teams criticized the videotape as not being representative of their activity. One way to eliminate this criticism was to pick the two most voluminous parts run by the work center as subjects to be taped. Since the teams were viewing the tapes and making their own recommendations, they felt good about the changes and recommendations.

Refining the videotaping organization further, two adjacent shifts teamed up to facilitate the part selections. The first shift changed from part A to part B, while the second shift videotaped their setup. When the setup was complete, the teams reversed their roles. The second shift gave the cameras to the first shift, and they became the setup team; the second shift changed from part B back to part A. This arrangement worked out quite well and was used by several other teams. The production schedule was impacted minimally and the few parts which were made off-schedule were saved for later use; since these were high volume parts, a production run of these parts was likely in the near future.

The videotaping process completed the data collection phase, and analyzing of the data began.

Analyze Data

The second step was to *analyze the data.* The team reviewed the videotapes in detail during this phase. Two issues were documented concurrently: a walking diagram illustrated the movements of each team member and an analysis chart detailed the methodology.

The walking diagram required getting a layout of the work center. Since there were several machines involved in the production lines, a 432 mm × 558 mm (17″ × 22″) scaled layout was chosen; one copy was needed for each team member. As the videotape was viewed, one team member drew the movements of the person being viewed onto the layout. The walking chart showed the movements of each team member from an overhead perspective (see Fig. 4.5.1).

Simultaneously, the team member being viewed on the tape, recorded the method steps on an analysis chart (see Fig. 4.5.2). Since a detailed elemental analysis was not the purpose of this documentation, work steps of 3- to 20-minute duration were recorded. The chronological time stamp from the video was used to determine the elemental time of each step. After a work step was identified, the team spent time reviewing and discussing it.

The work was defined as to whether it was preparation, replacement, or adjustment; each step included any combination of these activities or none at all. The purpose of this classification was to determine whether the step could be redefined and improved. The preparation, replacement, and adjustment activities were typically the ones in which the most improvement was possible.

Preparation was most commonly defined as motions of searching, selecting, finding, aligning, and transporting. Activities included searching for tools, fasteners, tooling, cart, pallets; waiting for fork trucks; checking machine specifications and setup requirements. Teams made the most progress when preparation activity was eliminated during setup. For the ideal setup, everything was already organized and on-hand, and team members did not have to leave the work center area for any reason.

Replacement included removal of hardware, such as tooling and fixtures, used in producing the previous part and included installation of hardware needed for producing the new part. Activities included removing and attaching items. If off-line equipment was available for presetup activity, replacement included moving out the currently used equipment and moving in the presetup equipment.

Adjustment included making those additional settings necessary to produce an acceptable product.

Marking whether each work step contained these activities provided for quick reference in future discussions.

Next, the timing of the work step was evaluated as to whether the work had to be done internally or externally. (Definitions of these terms were discussed earlier in the chapter.)

In order to reduce setup time, teams had to change what they were doing. As Earl Nightingale put it so well, “If you keep on doing what you’ve always done, you’re going to keep on getting what you’ve always got!”

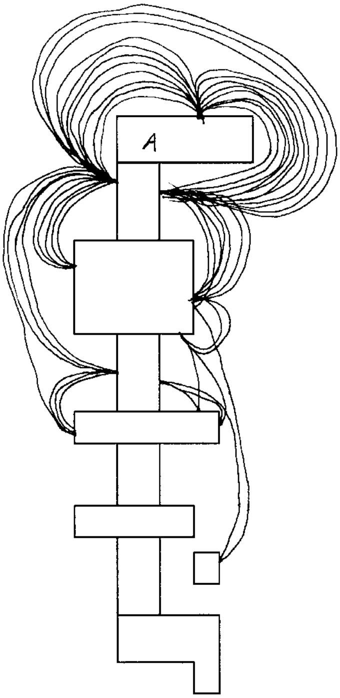

FIGURE 4.5.1 A representation of an actual walking chart for one team member during one setup. This person walked around machine A a total of 38 times during this one setup.

Analysis Chart

Project: ______________________ Date: ____________ Page: ___

Step No.	Description	Time		Activity			Timing		Improvements			Improvement Notes
		Video	Element	Prep.	Replace	Adjust	Inter	Exter	O	R	E	
	Video start time =	11:02 AM										
1	Lockout equipment.	11:04 AM	2				X			X		Position locks close to lockout station. [save 15 seconds]
2	Remove spindles from previous part and position spindles for new part.	11:14 AM	10		X	X	X		X	X	X	Use a setup cart; place old spindles on it instead of work bench. Have new spindles on cart & ready to go. Tighten holders to eliminate having to fiddle with them. [save 2 minutes]
3	Remove lockouts.	11:15 AM	1				X					
4	Run first part and measure.	11:18 AM	3			X	X	X	X	X	X	Use a template to lay over the part to eliminate use of tape measure. Tighten up machine bolts to eliminate looseness in holding the part. [save 30 seconds]

FIGURE 4.5.2 Analysis chart.

Develop Solutions

On the last portion of the analysis chart, the team began the third step of the team process, which was to *develop solutions.* Team members emphasized what they could do for themselves. Basics included organizing their activities before the setup, reducing the elements of the setup, and eliminating the adjustments after setup. If improvements were perceived in any of these three areas, a *X* was placed in the appropriate column on the analysis chart.

Organizing before the setup included addressing all of the work that could be accomplished prior to shutting the equipment down. In reviewing the analysis chart, each of those steps marked as *internal* was scrutinized. Each work step was evaluated as to when it had to be performed.

Any step, which could be performed prior to the setup, was prioritized accordingly. Teams strived to do as many steps as possible while the machinery was in operation; during internal time, members performed only those steps that required the machine to be shut down. Tools and fixtures were color-coded to make them easy to identify and control. A toolroom maintained tools on a regular schedule, and the tools were kept in stock or kept on a ready-to-run rack. A toolcart was used to have the tools and tooling readily available at the machine when the setup process began. Tools and dies were standardized so that they could run more than one type of job. This included standardizing holding fixtures to reduce changes and adjustments.

Method changes included reducing the time spent on the adjusting and test-running phase. Some method changes included using a preset positioning technique, part stops, limit switches, and automatic gauging. Teams strove to achieve a positive, repeatable positioning of tools and dies in which adjustments were not required and the first produced part was always a good one.

Teams ensured following key parts of the process by developing a good checklist. These lists included the required tools, materials, documentation, and procedures. The lists included optimum speeds, feeds, temperatures, pressure, and similar settings for given product and machines. Specific critical steps were itemized. One team that had access to a personal computer made a data file for their setup checklists; they updated this file as changes were noted.

Reviewing the walking chart brought additional organizing ideas to mind. Teams reduced walking by using a central control panel for electrical and compressed air lockouts; this eliminated walking to two different locations to lock out equipment. (These lockouts are required by federal Occupational Safety and Health Administration regulations; easy access to these lockout devices is often overlooked.) Also, they reduced walking by designing and buying a specialized setup cart to transport tooling and tools; this cart facilitated having their materials within hand reach of most setup activity. (Utility carts were available in supply catalogs servicing toolrooms and machine shops.) The chart illustrated problems with walking between work points too many times (see Fig. 4.5.1 as an example). After seeing this maze of walking patterns, team members worked to simplify the sequence of work steps and to coordinate their work duties closely.

Reducing the elements of the setup included reducing the time it took to perform the duties during the setup and eliminating activity during this process. By reviewing the walking chart and the analysis chart, teams strove to develop simultaneous activities, to improve clamping methods, and to improve replacement and installation. By using simultaneous activities, two team members worked together to avoid having someone walk from one side of the machine to the other.

Improved clamping methods addressed the issue that fasteners slowed down the whole process. Teams reviewed the need for tightness. Using one-turn methods were good substitutes for bolts; other alternatives included use of U-shaped washers, split-threads, and clamps. One-motion methods included cam clamps, spring stops, and vacuum suction. Other ideas included using wing nuts and hinged bolts with wing nuts.

Improved replacement and installation included reviewing the fastening technique. The function of the bolt was to fasten or position things. Some fastening functions were accomplished through levers or pneumatic hold-downs instead of bolts. For some positioning, pin stops were used. Teams made every effort to make setups a no-tool event by using knobs, handles, hand-wheels, and levers. Samples of these items were purchased in standard sizes and made available for teams to test.

Eliminating the adjustments after setup included finding methods and techniques to accomplish setting machinery correctly the first time. The objective was to set the machinery correctly the first time and to eradicate the need to adjust the equipment in later steps. The theory and method of robust design (Taguchi) can be used to improve the setting process. Some teams found that they eliminated most adjustments by calibrating the equipment on a scheduled basis and by being more accurate in setting tooling into the machinery.

Some teams found that they often completed their setup activity quickly, but then had to adjust over and over to accomplish the tolerances required by product specifications. By documenting the machine settings and using this data for setup, members reduced the frequency of adjustments being performed.

Specific comments on these three improvement areas (organize, reduce, and eliminate) were made in the improvement notes column of the analysis chart. An estimate of the time improvement resulting from this change was noted. To this point, the old method was reviewed and improvement recommendations noted on the chart. The work steps required to complete the setup were defined and new time estimates completed. The next phase was to organize these work steps.

Keeping with the spirit of having the team "do for themselves," the team used a paper template technique to organize the work steps; this approach reemphasized having the team provide their own service and not rely on others to do the work for them. Each work area, or specific machine center, was identified and a specific color assigned to it. Construction paper elements (scaled for the time involved) were cut for each work element regardless of which team member performed the work. A time line was developed for the entire setup and each member's duties were itemized in chronological order on an operator–machine chart (see Fig. 4.5.3).

As a measure of effectiveness in leveling the work load among team members, the team added the times of each individual work step. Referring to the operator–machine chart, the latest time shown, called chronological time, was multiplied by the team size. Comparing the total work required (the first calculated number) to this time indicated how well the team worked together to minimize setup time. As calculated for Fig. 4.5.3, the total of the individual work steps was 45 team-minutes; the total chronological time equaled 16 minutes times three team members or 48 team-minutes. The utilization ratio was calculated as $^{45}\!/_{48}$ or 94 percent. Due to interference between work elements and due to timing issues, it was difficult to achieve 100 percent.

After completing the operator–machine chart, the team worked to refine their working together to minimize the setup time. Most teams related well to a football team analogy: Just before a play, the football team huddled to get directions on the upcoming play. The setup team briefly discussed their plans before they moved into action. Knowing each team member's responsibility made the timing and coordination more effective.

The last of the steps was to pick and justify solutions.

Pick and Justify Solutions

When the team had the choice of several techniques to reduce the setup time, the team justified the chosen ideas by using time reduction, cost savings, safety, and quality. An improvement plan listing was helpful in documenting changes. Through group discussion, the items listed on the plan were developed into a schedule of improvements. Teams defined who was to do what, by when, and with what means; specific goals were clarified and set. Participation by everyone, including production, engineering, and maintenance personnel, was key to making improvements successful. Specific improvement plans were grouped into three categories: (1) small improvements that could be implemented right away, (2) medium improvements that required minimal time and money, and (3) large improvements that required equipment redesign, technical studies, or other time- and/or expense-consuming elements.

SMALL IMPROVEMENTS were implemented as soon as the team members agreed to implementation. To share a proposed change, a team member attached a paper tag to the proposed change; the proposed change was described on this tag. During a joint shift meeting, the tags

Operator–Machine Chart

Time (min)	Position or person A	Position or person B	Position or person C
1	Lockout equipment.	Move cart in place.	WAIT
2		WAIT	Move in new pallet.
3	Remove spindles.		Run 1st cycle of new parts into feeder and adjust feeder for new part size.
4	Position new spindles.	Position new spindles.	
5			
6			
7			
8			
9			
10			Help with spindles.
11			
12			
13	Remove lock nuts.	Check side rails.	Ready pallet at end.
14	Run first part and measure.	Run first part and measure.	
15			WAIT
16			
17			

FIGURE 4.5.3 Operator–machine chart.

were discussed and input requested. If everyone agreed to the change, someone accepted the responsibility of following up on the idea and implementing it. Any ideas which were procedural were put into action immediately if affected departments and employee teams agreed. One team labeled their racks containing label stock to reduce the time lost in searching for a specific item. Other teams designed setup sheets and began collecting and recording machine-setting data. Simple method changes were incorporated by all teams. One team set up equipment off line; they marked the floor to indicate the correct positioning of the equipment and saved several minutes of positioning time.

MEDIUM IMPROVEMENTS which did not involve maintenance and engineering functions were approved by production supervision for implementation. There was an approval level of up to $250. Several teams designed and had setup carts fabricated. Most of the teams replaced standard bolts and screws with no-tool alternatives such as hand wheels, hand knobs, wing nuts, and so on.

LARGE IMPROVEMENTS took more effort and resources. Any recommendation which required spending an amount of more than $250 required cost justification. Since the cost justification technique varied with each particular type of savings, the industrial engineer facilitator and accounting personnel assisted the teams in making calculations. One team installed hose reels above their work station to eliminate getting and rewinding their air hoses. Another team moved an air line which caused reaching problems (the shorter team member had to go get a ladder to operate the valve). One team, which operated highly automated mechanisms, had all of the equipment calibrated and adjusted by the manufacturer.

Now that the team's efforts resulted in the implementation of their ideas and recommendations, they followed up periodically to make sure that they were not reverting back to old practices. Teams strove to solve lingering issues by following up on any open issue.

RESULTS AND FUTURE ACTIONS

In this case study, the results from four production lines were documented. Each of these four lines was operated by 3 employee teams, one team on each shift. The operational data was as listed in Table 4.5.1 following:

Those teams that used the key elements of setup reduction on a continual basis accomplished a higher degree of success. The fundamental principles which they utilized included the following:

USE OF THE ACTION LOG. The action log documented specific action plans discussed during the meetings. As soon as someone recognized a point which must be followed up, it was entered into the log; a team member volunteered to coordinate the item and agreed upon a goal date. At the beginning of each meeting, any open items on the list were reviewed, and the status was discussed. At the end of each meeting, those items were reviewed which required further action and follow-up.

IMPLEMENTATION OF MEASURABLE SETTINGS. Teams found much time was spent setting up for a first run of the part, then making adjustments to the settings and running another part. This cycle continued until an acceptable part was made. In making the initial settings to specific measurements, most adjustments were eliminated. In conjunction with specific settings, teams decided that the best time to record the best machine settings was when a good product was being produced. They documented speeds, feeds, temperature settings, and any other appropriate operational measurement. This data was organized onto a setup chart which could be updated as required and printed out for reference.

USE OF THE WALKING CHART. The walking chart facilitated each team member's visualization of the amount of movement during setup. Immediately upon completing this diagram, most members came up with ideas on reducing the distance covered while performing the work required.

USE OF CARTS. In several cases, the walking diagram was the convincing concept which led the teams into incorporating carts. Design of the cart depended on the operation involved. Once the design was formulated and the carts fabricated, members found the value in having their tools and tooling at hand.

NO-TOOL CONCEPT. Several teams struggled with eliminating the use of all tools during setup. Those teams that succeeded in eliminating tools eliminated the need to search for tools, eliminated the placement of tools, and eliminated keeping track of tools.

WORKING AS A TEAM. Members made sure to be critical of solution choices (not people). It took a leader who believed in the concept to sell an idea and to get others to follow. Ideas just lay there if someone did not develop and implement them.

TABLE 4.5.1 Case Study Results from Four Production Lines

Production line	Setup time	Quality	Productivity	Down time
#1	–68%	no change	+10%	–12%
#2	–28%	no change	no change	–6%
#3	–47%	no change	+12%	–13%
#4	–69%	no change	no change*	no change*

* *Note:* As the setup time was reduced, the lot sizes were reduced such that the same amount of time was spent in setups. This was not the original plan when the training began. However, there were advantages to reduced lot sizes: the customer's response time improved significantly.

One issue related to setups which overlapped shifts. When reducing the setup time to less than 20 minutes, some teams chose to complete the setup even if it went into the next shift. By the time they explained how they had progressed and the next shift checked the completeness of the setup, the work could have been accomplished. So, it was more economical to pay the overtime to the first shift to complete the setup correctly and thoroughly.

If continuing the setup into the next shift was not a viable option, establishing a routine setup that all teams followed was the next-best solution. Using the same routine facilitated the oncoming shift's ability to pick right up where the previous shift left off. This technique reduced the need to check what the previous shift completed and to determine what setup steps were required.

One management support issue was related to the first-line supervisor. In those cases where their immediate supervisors embraced the concept and participated in at least 50 percent of the training sessions, the team surpassed its goals. There was one case in which a team surpassed expectations without having strong supervisory support and backing; this team had a team member who was their informal leader, and this member became the internal motivator.

The last major issue related to the use of the time saved by reducing setup time. As setup time requirements were reduced, additional production time became available. If the company did not need the expanded capacity of that machine, employees became concerned for their security. Employees needed to know whether they would lose their present overtime income, or if they would lose their job, by succeeding in reducing setup requirements. Support for this quick setup concept was forthcoming from the team members when these issues were addressed. In this case, the company made the commitment that no employee would lose his or her job due to implementation of quick setups.

One of the most revealing issues which affected the teams was the employee turnover during the training process. During the training cycle, members left for other positions within the company or for other opportunities. New members were added to the team to replace the ones who left. Now, there were members who understood the training and there were those who needed additional orientation so they could understand where the team was with regard to quick setup activity. When there was a strong support for the training process within the team, other members provided the initiative and emphasis to maintain the setup effort. Otherwise, the training was temporarily suspended while the new team members gained the skill level necessary to be contributing members of quick setups.

In summary, achieving quick setups was possible when management and team members worked together, and the effort was maintained when the proper motivation was provided. The industrial engineer played a leading role in the success of the teams by sharing the use of industrial engineering tools and by assisting the teams in meeting their objectives.

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BIOGRAPHY

William Morgan Brown, P.E., works in private industry. He earned a B.S. in industrial engineering from Clemson University and an M.S. in industrial and systems engineering from

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SECTION 5

WORK MEASUREMENT AND TIME STANDARDS

Source: MAYNARD'S INDUSTRIAL ENGINEERING HANDBOOK

CHAPTER 5.1

MEASUREMENT OF WORK

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This chapter will introduce the uses and methods of measuring work, with emphasis on predetermined time systems such as MTM-1, WF, MODAPTS, BMT, MTM-2, MTM-3, GPD, and MOST. Examples of applications are shown, and the benefits and limitations of predetermined time systems are discussed.

INTRODUCTION

Work measurement is used to develop standard times needed to perform operations. *Time standards* have traditionally been defined as the time required by an average skilled operator, working at a normal pace, to perform a specified task using a prescribed method, allowing time for personal needs, fatigue, and delay. Time standards, work standards, and standards of all types are critical pieces of management information that apply to manufacturing, assembly, clerical, and other work.

Standards provide information essential for the successful operation of an organization:

Data for scheduling. Production schedules cannot be set, nor can delivery dates be promised, unless times for all operations are known.

Data for staffing. The number of workers required cannot accurately be determined unless the time required to process the existing work is known. Continuing management of the workforce requires the use of labor variance reports. Labor variance reports are also useful for determining changes in work methods, especially the subtle or incremental changes.

Data for line balancing. The correct number of workstations for optimum work flow depends on the processing time, or standard, at each workstation. Operation times and setup times are key pieces of this information.

Data for materials requirement planning. MRP systems cannot operate properly without accurate work standards.

Data for system simulation. Simulation models cannot accurately simulate operation unless times for all operations are known.

Data for wage payment. To be equitable, wages generally must be related to performance. Comparing expected performance with actual performance requires the use of work standards.

Data for costing. Ultimately, the profitability of an organization lies in its ability to sell products for more than it costs to produce them. Work standards are necessary for determining not only the labor component of costs, but also the correct allocation of production costs to specific products.

Data for employee evaluation. In order to assess whether individual employees are performing as well as they should, a performance standard is necessary against which to measure the level of performance.

DEFINITION OF STANDARD TIME

To reiterate, the *standard time* is the time required by an average skilled operator, working at a normal pace, to perform a specified task using a prescribed method, allowing time for personal needs, fatigue, and delay. Some key factors of this definition are the understanding of an average skilled operator, the concept of normal pace, the reliance on prescribed method, and the designation of the allowance.

An *average skilled operator* is an operator who is representative of the people performing the task. The average skilled operator is neither the best nor the worst, but someone who is skilled in the job and can perform it consistently throughout the entire workday.

The *normal pace* is a rate of work that can be maintained for an entire workday. It is neither too fast nor too slow. It is the pace of an average skilled worker. Rarely will any worker perform at the normal pace for an entire workday. Sometimes the worker will perform faster than the normal pace. Sometimes the worker will perform slower than the normal pace. The normal pace represents an ideal that the industrial engineer judges the average worker should be able to maintain long term.

Another key part of the definition is the phrase relating to *prescribed method.* Work standards measure the time required to correctly perform defined tasks. Part of the definition must include a statement regarding the quality of the work performed.

All workers have personal needs that must be attended to. Workers sometimes become tired as the workday progresses. When developing a time standard, an *allowance* must be made for these factors. Additionally, there will be occasional unexpected and often uncontrollable delays, such as material shortages or equipment breakdowns, and these, too, must be allowed for. The personal, fatigue, and delay (PFD) factors, depending on the nature of the work being performed, can be significant, typically representing from 10 to 15 percent of the workday. (For further information on allowances, see Chap. 5.5.)

MEASURING WORK

Standards have traditionally been developed in one of three major ways.

1. The first of these is *estimation,* which can be done in either of two ways. Sometimes the time required is provided via a SWAG [1], whereby an individual who is believed to be knowledgeable about the task examines the work to be completed and then states, "It ought to take about that many hours to get all the pieces run." Sometimes it does. Sometimes it does not. Sometimes work gets completed early. Other times bottlenecks develop and schedules are missed. The other commonly used method of estimation involves the use of historical data. Prior runs are examined and actual times and production quantities are used to develop a historical standard. The danger with historical standards lies in Parkinson's Law [2] as applied to industrial engineering.

2. Standards are also set using direct observation and measurement. The three common methods for setting standards using direct observation are *time study, work sampling,* and *physiological work measurement.* Time study is defined as follows:

> Time study is the analysis of a given operation to determine the elements of work required to perform it, the order in which these elements occur, and the times which are required to perform them effectively [3].

Time study involves the use of a timing device, study of the existing work method, recording observed times, rating the subject's performance compared with normal pace, and adding the PFD allowance. Time study is most effective for developing standards for highly repetitive tasks that have relatively short cycle times. For a description of stopwatch time study, see Chap.17.2. When work is nonrepetitive and has relatively long cycle times (e.g., some clerical and maintenance tasks), then work sampling is an appropriate method for setting standards.

> A work sampling study consists of a large number of observations taken at random intervals; in taking the observations, the state or condition of the object of study is noted, and this state is classified into predefined categories of activity pertinent to the particular work situation. From the proportions of observations in each category, inferences are drawn concerning the total work activity under study [4].

A third way to directly measure work performed is by physiological means. This is based on the fact that work is equal to force times distance. Energy is required to perform work. Physical work results in changes in oxygen consumption, heart rate, pulmonary ventilation, body temperature, and lactic acid concentration in the blood. Although some of these factors are only slightly affected by muscular activity, there is a linear correlation between heart rate, oxygen consumption and total ventilation, and the physical work performed by an individual. Of these three, the first two—heart rate and oxygen consumption—are most widely used for measuring the physiological cost of human work [5].

Many studies have shown that the difference between well-trained workers and beginners on a job is significant. The physiological cost to the beginner would be greater when the beginner attempts to produce at the normal pace. Physiological measurements are used to compare the cost to the worker for performing varying tasks [6].

3. The third general way of setting work standards is through the use of *standard data systems.* Mil-Std 1567 [7] defined standard data as "a compilation of all the elements that are used for performing a given class of work with normal elemental time values for each element. The data are used as a basis for determining time standards on work similar to that from which the data were determined without making actual time studies." *Standard data* is the term used to describe time data for groups of motions rather than single motions. Such data are used to set standard times for new work without having to take complete and detailed studies of the work. They are compiled from existing detailed studies of manual work and are arranged in the form of tables, graphs, and formulas for ready use. Knowledge of how the new job must be done makes it possible to select the appropriate time data from these records to obtain the proper standard time for the job [8].

There are two types of standard data. One is what is often referred to as *macroscopic standard data.*

> Many operations in a given plant have several common elements. The element, "walking," for example, is a component of many different jobs. Diverse activities such as painting, handling or working on a site invariably involve an element of "walking." When these activities are timed, the same common element is in fact timed again and again. The job of the work study analyst would therefore be made much easier if the analyst had at the disposal a set of data from which he or she could readily derive standard times for these common work elements without necessarily going into the process of timing each one [9].

Macroscopic standard data takes advantage of similarities of activities within like families of operations and uses those similarities to develop standards for related activities. Standard data can reduce the time and labor required to set standards [10]. Chapter 5.3 deals with these types of standards in detail. The other type of standard data is what might be called *microscopic standard data,* which is the major focus of this chapter. This type of standard data is also often referred to as *predetermined time systems.* It is a motion-based method of work measurement.

> By carefully describing all of the motions required to perform a particular job, the analyst will have to carefully study the method being used to perform the job. When the motions required to complete the work have been identified, the standard can be set. In predetermined time systems, each motion that is described and coded has a specific time allowed for its completion. By completely identifying all of the motions required, the entire time for a sequence of motions or for an entire operation can be synthesized. Once the allowance is applied, an accurate time standard can be issued. This procedure, of course, is based on the assumption that the correct motions have been identified before the times are assigned [11].

A wide variety of predetermined time systems exist. They will be described in more detail subsequently. Regardless of the specific system selected, they all are used in a similar fashion. Initially, the task being studied has to be precisely defined in terms of the motions involved. This requires a complete understanding of the operation. Once the motions are defined, then times for individual motions are retrieved from the system's database. The individual motion times are combined, and an appropriate allowance is incorporated. The resulting total is the time standard for the task.

ADVANTAGES AND LIMITATIONS OF PTS

Predetermined time systems have four major advantages (and some limitations as well). Benefits include the following:

1. All predetermined time systems require a complete methods analysis prior to setting the standard. Each motion must be identified. Obvious methods problems and other inefficiencies are readily identified by detailed study of the work method being used. The resulting analysis yields a well-documented procedure for performing the task. New jobs are forced to establish a sound, well-thought-out method.
2. Predetermined time systems do not require the analyst to perform performance rating. This eliminates some subjectivity from the resulting standard and provides a more consistent standard.
3. In order to develop work standards using a direct observation method, the work must be measured while it is being performed. Predetermined time systems allow the analyst to visualize the work and synthesize the standard even if the task is still in the planning phase.
4. Predetermined time systems provide information about learning time. The development of learning curves and their subsequent application is an essential part of determining the cost of a new product or service. (See also Chaps. 17.5 and 17.10.)

Although significant benefits are associated with predetermined time standards, there are also some limitations. A major disadvantage is the difficulty encountered with machine-paced operations. Most of the predetermined systems were designed for human motion times, not machine times. Some of the systems have been designed for specific type of work, such as clerical or sewing operations, and the motions defined within the systems do not transfer well to other types of work. Predetermined time systems have many definitions and rules associated with the proper application of times. Whether this is a disadvantage is debatable, but a significant amount of training is required to enable individuals to competently apply most of the systems.

PREDETERMINED TIME SYSTEMS

Predetermined time systems provide information about manual work cycles in terms of basic human motions. There are differences between the criteria adopted for the classification of these motions. Broadly speaking, there are two main sets:

1. Object-related classification
2. Behavior-related classification

In an object-related system, reference may be made to characteristics of parts or to the nature of the surrounding conditions. Behavior-related systems classify motions according to what they look like to an observer [12].

Another way to classify predetermined time systems is as motion-based, action-based, or activity-based. *Motion-based* encompasses all those systems that are made up of basic motions—time elements that cannot be broken down into smaller elements. *Action-based* are such systems that consist of combining basic motions into actions. *Activity-based* are systems consisting of elements that are combinations of basic motions or (in most cases) action elements. Activity-based elements are then put together in a sequence representing a complete activity, such as “move object from A to B” or “fasten screw with screwdriver.”

Some examples of motion-based predetermined time systems are presented first.

METHODS TIME MEASUREMENT (MTM-1)

The most widely publicized system of performance rating ever developed was presented in *Time and Motion Study* by Lowry, Maynard, and Stegemerten (1940) [13]. The rating system was based on four factors: skill, effort, consistency, and performance. Maynard and Stegemerten teamed with John Schwab to expand this idea into *methods time measurement* (MTM) [14]. (This is now known as MTM-1.) According to Robert Rice, this method is the most widely used system of predetermined times [15]. Maynard and associates performed many micromotion studies to come up with their standard elements and times. Because MTM was readily available, it is not surprising that it is the most frequently used—and the most frequently imitated—of all the systems. Standard MTM-1 data is shown in Fig. 5.1.1.

MTM-1 is a procedure for analyzing any manual operation or method by breaking out the basic motions required to perform it and assigning to each a predetermined standard time based on its nature and the conditions under which it is made [16]. *Reach* is the most common or basic MTM-1 motion. Other motions include the following:

Move. The predominant purpose is to transport an object to a destination.

Turn. The hand is turned or rotated about the long axis of the forearm.

Position. Motion is employed to align, orient, and/or engage one object with another.

Grasp. The main purpose is to secure sufficient control of one or more objects with the fingers or the hand.

Release. The operator relinquishes control of an object.

Disengage. Contact between two objects is broken.

Eye times. The eyes direct hand or body motions.

Body motions. Motions are made by the entire body, not just the hands, fingers, or arms.

Shown in Fig. 5.1.2 is a sample MTM-1 analysis detailing the motions required to attach a bank check to a bill invoice [17].

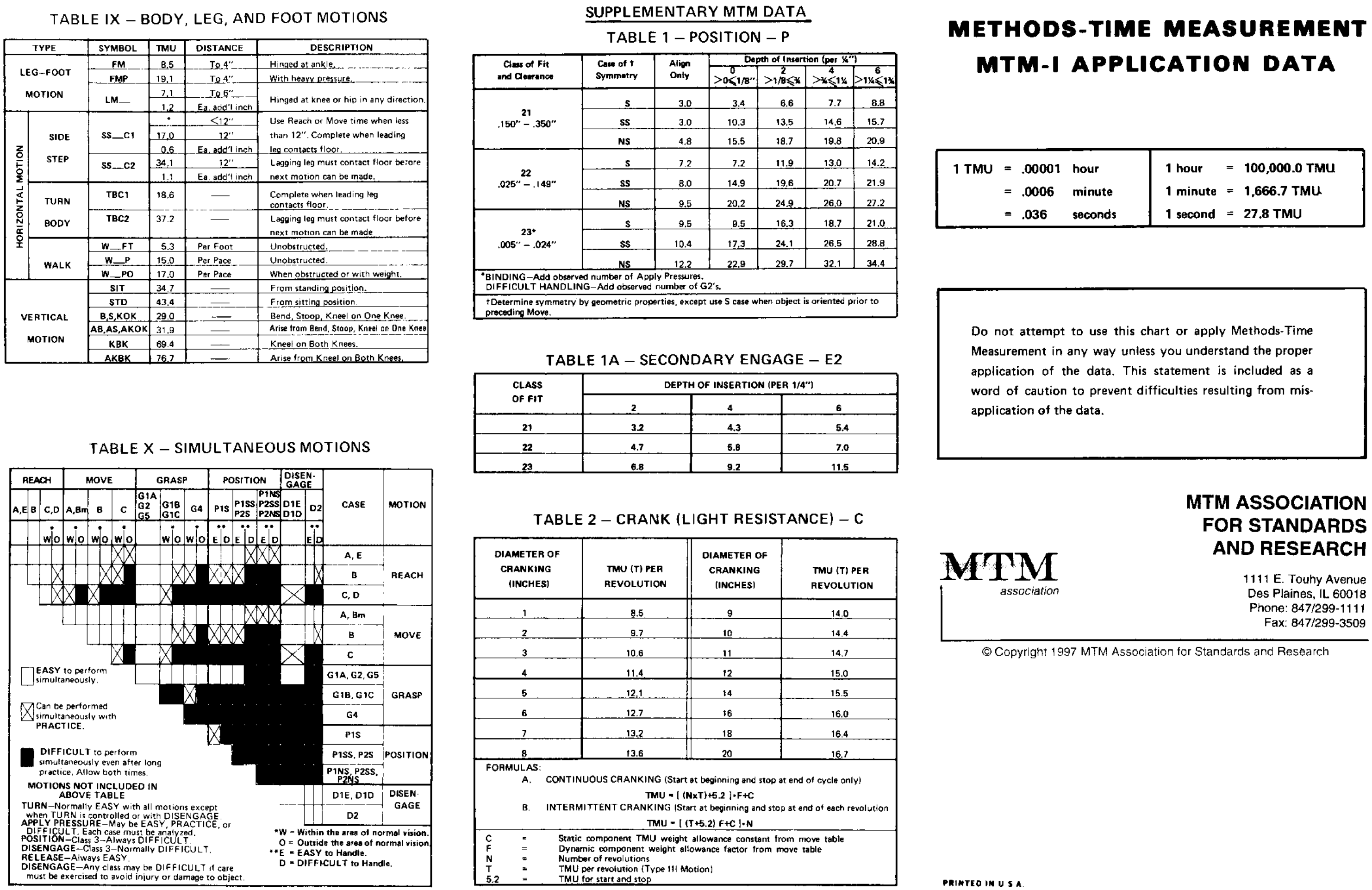

TABLE IX – BODY, LEG, AND FOOT MOTIONS

TYPE		SYMBOL	TMU	DISTANCE	DESCRIPTION
LEG–FOOT MOTION		FM	8.5	To 4″	Hinged at ankle.
		FMP	19.1	To 4″	With heavy pressure.
		LM__	7.1	To 6″	Hinged at knee or hip in any direction.
			1.2	Ea. add'l inch	
HORIZONTAL MOTION	SIDE STEP	SS__C1	*	<12″	Use Reach or Move time when less than 12″. Complete when leading leg contacts floor.
			17.0	12″	
			0.6	Ea. add'l inch	
		SS__C2	34.1	12″	Lagging leg must contact floor before next motion can be made.
			1.1	Ea. add'l inch	
	TURN BODY	TBC1	18.6	——	Complete when leading leg contacts floor.
		TBC2	37.2	——	Lagging leg must contact floor before next motion can be made
	WALK	W__FT	5.3	Per Foot	Unobstructed.
		W__P	15.0	Per Pace	Unobstructed.
		W__PO	17.0	Per Pace	When obstructed or with weight.
VERTICAL MOTION		SIT	34.7	——	From standing position.
		STD	43.4	——	From sitting position.
		B,S,KOK	29.0	——	Bend, Stoop, Kneel on One Knee.
		AB,AS,AKOK	31.9	——	Arise from Bend, Stoop, Kneel on One Knee
		KBK	69.4	——	Kneel on Both Knees.
		AKBK	76.7	——	Arise from Kneel on Both Knees.

TABLE X – SIMULTANEOUS MOTIONS

REACH				MOVE						GRASP					POSITION						DISEN-GAGE			CASE	MOTION
A,E	B	C,D		A,Bm		B		C		G1A G2 G5	G1B G1C		G4		P1S		P1SS P2S		P1NS P2SS P2NS		D1E D1D	D2			
		*W	O	*W	O	*W	O	*W	O		*W	O	*W	O	**E	D	**E	D	**E	D		**E	D		
☐	☐	☐	☐	☐	☐	☐	☐	☒	☒	☐	☐	☐	☐	☐	☐	☐	☐	☒	☒	☒	☐	☐	☐	A, E	REACH
	☐	☐	☒	☐	☐	☐	☒	☒	■	☐	☐	☒	☒	■	☒	☒	☒	■	■	■	☐	☐	☒	B	
		☐	☒	☒	■	☒	■	■	■	☐	☒	■	■	■	■	■	■	■	■	■	☒	■	■	C, D	
				☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☒	☒	☒	☐	☐	☐	A, Bm	MOVE
						☐	☐	☐	☐	☐	☐	☒	☒	■	☒	☒	☒	■	■	■	☐	☐	☒	B	
								☒	■	☐	☒	■	■	■	■	■	■	■	■	■	☒	■	■	C	
										☐	☐	☐	☐	☐	☐	☐	☐	■	■	■	☐	■	■	G1A, G2, G5	GRASP
											■	■	☒	■	■	■	■	■	■	■	■	■	■	G1B, G1C	
													■	■	■	■	■	■	■	■	■	■	■	G4	
															☒	■	■	■	■	■	■	■	■	P1S	POSITION
																	■	■	■	■	■	■	■	P1SS, P2S	
																			■	■	■	■	■	P1NS, P2SS, P2NS	
																						☐	☐	D1E, D1D	DISEN-GAGE
																						☐	☐	D2	

☐ EASY to perform simultaneously.

☒ Can be performed simultaneously with PRACTICE.

■ DIFFICULT to perform simultaneously even after long practice. Allow both times.

MOTIONS NOT INCLUDED IN ABOVE TABLE

TURN—Normally EASY with all motions except when TURN is controlled or with DISENGAGE.
APPLY PRESSURE—May be EASY, PRACTICE, or DIFFICULT. Each case must be analyzed.
POSITION—Class 3—Always DIFFICULT.
DISENGAGE—Class 3—Normally DIFFICULT.
RELEASE—Always EASY.
DISENGAGE—Any class may be DIFFICULT if care must be exercised to avoid injury or damage to object.

*W = Within the area of normal vision.
O = Outside the area of normal vision.
**E = EASY to Handle.
D = DIFFICULT to Handle.

SUPPLEMENTARY MTM DATA

TABLE 1 – POSITION – P

Class of Fit and Clearance	Case of † Symmetry	Align Only	Depth of Insertion (per ¼″)			
			0 >0≤1/8″	2 >1/8≤¾	4 >¾≤1¼	6 >1¼≤1¾
21 .150″ – .350″	S	3.0	3.4	6.6	7.7	8.8
	SS	3.0	10.3	13.5	14.6	15.7
	NS	4.8	15.5	18.7	19.8	20.9
22 .025″ – .149″	S	7.2	7.2	11.9	13.0	14.2
	SS	8.0	14.9	19.6	20.7	21.9
	NS	9.5	20.2	24.9	26.0	27.2
23* .005″ – .024″	S	9.5	9.5	16.3	18.7	21.0
	SS	10.4	17.3	24.1	26.5	28.8
	NS	12.2	22.9	29.7	32.1	34.4

*BINDING—Add observed number of Apply Pressures.
DIFFICULT HANDLING—Add observed number of G2's.

†Determine symmetry by geometric properties, except use S case when object is oriented prior to preceding Move.

TABLE 1A – SECONDARY ENGAGE – E2

CLASS OF FIT	DEPTH OF INSERTION (PER 1/4″)		
	2	4	6
21	3.2	4.3	5.4
22	4.7	5.8	7.0
23	6.8	9.2	11.5

TABLE 2 – CRANK (LIGHT RESISTANCE) – C

DIAMETER OF CRANKING (INCHES)	TMU (T) PER REVOLUTION	DIAMETER OF CRANKING (INCHES)	TMU (T) PER REVOLUTION
1	8.5	9	14.0
2	9.7	10	14.4
3	10.6	11	14.7
4	11.4	12	15.0
5	12.1	14	15.5
6	12.7	16	16.0
7	13.2	18	16.4
8	13.6	20	16.7

FORMULAS:

A. CONTINUOUS CRANKING (Start at beginning and stop at end of cycle only)

$$TMU = [(N \times T) + 5.2] \cdot F + C$$

B. INTERMITTENT CRANKING (Start at beginning and stop at end of each revolution

$$TMU = [(T + 5.2) F + C] \cdot N$$

C = Static component TMU weight allowance constant from move table
F = Dynamic component weight allowance factor from move table
N = Number of revolutions
T = TMU per revolution (Type III Motion)
5.2 = TMU for start and stop

METHODS-TIME MEASUREMENT
MTM-I APPLICATION DATA

1 TMU = .00001 hour		1 hour = 100,000.0 TMU
= .0006 minute		1 minute = 1,666.7 TMU
= .036 seconds		1 second = 27.8 TMU

Do not attempt to use this chart or apply Methods-Time Measurement in any way unless you understand the proper application of the data. This statement is included as a word of caution to prevent difficulties resulting from misapplication of the data.

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FIGURE 5.1.1 MTM data card.

TABLE I – REACH – R

Distance Moved Inches	Time TMU A	Time TMU B	Time TMU C or D	Time TMU E	Hand In Motion A	Hand In Motion B	CASE AND DESCRIPTION
3/4 or less	2.0	2.0	2.0	2.0	1.6	1.6	A Reach to object in fixed location, or to object in other hand or on which other hand rests.
1	2.5	2.5	3.6	2.4	2.3	2.3	
2	4.0	4.0	5.9	3.8	3.5	2.7	
3	5.3	5.3	7.3	5.3	4.5	3.6	B Reach to single object in location which may vary slightly from cycle to cycle.
4	6.1	6.4	8.4	6.8	4.9	4.3	
5	6.5	7.8	9.4	7.4	5.3	5.0	
6	7.0	8.6	10.1	8.0	5.7	5.7	
7	7.4	9.3	10.8	8.7	6.1	6.5	C Reach to object jumbled with other objects in a group so that search and select occur.
8	7.9	10.1	11.5	9.3	6.5	7.2	
9	8.3	10.8	12.2	9.9	6.9	7.9	
10	8.7	11.5	12.9	10.5	7.3	8.6	
12	9.6	12.9	14.2	11.8	8.1	10.1	
14	10.5	14.4	15.6	13.0	8.9	11.5	D Reach to a very small object or where accurate grasp is required.
16	11.4	15.8	17.0	14.2	9.7	12.9	
18	12.3	17.2	18.4	15.5	10.5	14.4	
20	13.1	18.6	19.8	16.7	11.3	15.8	
22	14.0	20.1	21.2	18.0	12.1	17.3	E Reach to indefinite location to get hand in position for body balance or next motion or out of way.
24	14.9	21.5	22.5	19.2	12.9	18.8	
26	15.8	22.9	23.9	20.4	13.7	20.2	
28	16.7	24.4	25.3	21.7	14.5	21.7	
30	17.5	25.8	26.7	22.9	15.3	23.2	
Additional	0.4	0.7	0.7	0.6			TMU per inch over 30 inches

TABLE II – MOVE – M

Distance Moved Inches	Time TMU A	Time TMU B	Time TMU C	Hand In Motion B	Wt. Allowance Wt. (lb.) Up to	Wt. Allowance Dynamic Factor	Wt. Allowance Static Constant TMU	CASE AND DESCRIPTION
3/4 or less	2.0	2.0	2.0	1.7				
1	2.5	2.9	3.4	2.3	2.5	1.00	0	
2	3.6	4.6	5.2	2.9				A Move object to other hand or against stop.
3	4.9	5.7	6.7	3.6	7.5	1.06	2.2	
4	6.1	6.9	8.0	4.3				
5	7.3	8.0	9.2	5.0	12.5	1.11	3.9	
6	8.1	8.9	10.3	5.7				
7	8.9	9.7	11.1	6.5	17.5	1.17	5.6	
8	9.7	10.6	11.8	7.2				B Move object to approximate or indefinite location.
9	10.5	11.5	12.7	7.9	22.5	1.22	7.4	
10	11.3	12.2	13.5	8.6				
12	12.9	13.4	15.2	10.0	27.5	1.28	9.1	
14	14.4	14.6	16.9	11.4				
16	16.0	15.8	18.7	12.8	32.5	1.33	10.8	
18	17.6	17.0	20.4	14.2				
20	19.2	18.2	22.1	15.6	37.5	1.39	12.5	
22	20.8	19.4	23.8	17.0				C Move object to exact location.
24	22.4	20.6	25.5	18.4	42.5	1.44	14.3	
26	24.0	21.8	27.3	19.8				
28	25.5	23.1	29.0	21.2	47.5	1.50	16.0	
30	27.1	24.3	30.7	22.7				
Additional	0.8	0.6	0.85		TMU per inch over 30 inches			

TABLE III A – TURN – T

Weight	30°	45°	60°	75°	90°	105°	120°	135°	150°	165°	180°
	Time TMU for Degrees Turned										
Small – 0 to 2 Pounds	2.8	3.5	4.1	4.8	5.4	6.1	6.8	7.4	8.1	8.7	9.4
Medium – 2.1 to 10 Pounds	4.4	5.5	6.5	7.5	8.5	9.6	10.6	11.6	12.7	13.7	14.8
Large – 10.1 to 35 Pounds	8.4	10.5	12.3	14.4	16.2	18.3	20.4	22.2	24.3	26.1	28.2

TABLE III B – APPLY PRESSURE – AP

FULL CYCLE SYMBOL	FULL CYCLE TMU	FULL CYCLE DESCRIPTION	COMPONENTS SYMBOL	COMPONENTS TMU	COMPONENTS DESCRIPTION
APA	10.6	AF + DM + RLF	AF	3.4	Apply Force
			DM	4.2	Dwell, Minimum
APB	16.2	APA + G2	RLF	3.0	Release Force

TABLE IV – GRASP – G

TYPE OF GRASP	Case	Time TMU	DESCRIPTION	
PICK-UP	1A	2.0	Any size object by itself, easily grasped	
	1B	3.5	Object very small or lying close against a flat surface	
	1C1	7.3	Diameter larger than 1/2"	Interference with Grasp on bottom and one side of nearly cylindrical object.
	1C2	8.7	Diameter 1/4" to 1/2"	
	1C3	10.8	Diameter less than 1/4"	
REGRASP	2	5.6	Change grasp without relinquishing control	
TRANSFER	3	5.6	Control transferred from one hand to the other.	
SELECT	4A	7.3	Larger than 1" x 1" x 1"	Object jumbled with other objects so that search and select occur.
	4B	9.1	1/4" x 1/4" x 1/8" to 1" x 1" x 1"	
	4C	12.9	Smaller than 1/4" x 1/4" x 1/8"	
CONTACT	5	0	Contact, Sliding, or Hook Grasp.	

EFFECTIVE NET WEIGHT			
Effective Net Weight (ENW)	No. of Hands	Spatial	Sliding
	1	W	$W \times F_c$
	2	W/2	$W/2 \times F_c$

W = Weight in pounds
F_c = Coefficient of Friction

TABLE V – POSITION* – P

CLASS OF FIT		Symmetry	Easy To Handle	Difficult To Handle
1–Loose	No pressure required	S	5.6	11.2
		SS	9.1	14.7
		NS	10.4	16.0
2–Close	Light pressure required	S	16.2	21.8
		SS	19.7	25.3
		NS	21.0	26.6
3–Exact	Heavy pressure required.	S	43.0	48.6
		SS	46.5	52.1
		NS	47.8	53.4

SUPPLEMENTARY RULE FOR SURFACE ALIGNMENT	
P1SE per alignment: >1/16 ≤1/4"	P2SE per alignment: ≤1/16"

*Distance moved to engage—1" or less.

TABLE VI – RELEASE – RL

Case	Time TMU	DESCRIPTION
1	2.0	Normal release performed by opening fingers as independent motion.
2	0	Contact Release

TABLE VII – DISENGAGE – D

CLASS OF FIT	HEIGHT OF RECOIL	EASY TO HANDLE	DIFFICULT TO HANDLE
1–LOOSE–Very slight effort, blends with subsequent move.	Up to 1"	4.0	5.7
2–CLOSE–Normal effort, slight recoil.	Over 1" to 5"	7.5	11.8
3–TIGHT–Considerable effort, hand recoils markedly.	Over 5" to 12"	22.9	34.7

SUPPLEMENTARY

CLASS OF FIT	CARE IN HANDLING	BINDING
1– LOOSE	Allow Class 2	————
2– CLOSE	Allow Class 3	One G2 per Bind
3– TIGHT	Change Method	One APB per Bind

TABLE VIII – EYE TRAVEL AND EYE FOCUS – ET AND EF

Eye Travel Time = $15.2 \times \frac{T}{D}$ TMU, with a maximum value of 20 TMU.

where T = the distance between points from and to which the eye travels.
D = the perpendicular distance from the eye to the line of travel T.

Eye Focus Time = 7.3 TMU.

SUPPLEMENTARY INFORMATION

– Area of Normal Vision = Circle 4" in Diameter 16" from Eyes

– Reading Formula = 5.05 N Where N = The Number of Words.

FIGURE 5.1.1 MTM data card. *(Continued)*

MTM ANALYSIS

Organization: Consolidated Enterprises, Inc. Date: May 1, 1998

Operation: Attach Bank Check to Bill Invoice System: MTM-1

Analyst: Robert Wayne Atkins, P.E. Study No: 1 Page 1 of 1

Left Hand Description	F	Motion	TMU	Motion	F	Right Hand Description
Reach to Bill Invoice		(R5B)	10.1	R8B		Reach to Bank Check
Grasp Bill Invoice		G1B	3.5			
			3.5	G1B		Grasp Bank Check
Lift Invoice Up Off Desk		(M4B)	11.1	M7C		Move Check to Invoice
			9.1	P1SSE		Position Check to Invoice
Grasp Check at Corner		G3	5.6	G3		Release Check
			12.2	R9C		Reach to Paper Clip Holder
			9.1	G4A		Grasp One Paper Clip
			12.7	M9C		Move Paper Clip to Check
			—	T90S/		Turn Paper Clip
			25.3	P2SSD		Position Clip on Check/Inv.
			2.0	RL1		Release Clip
ile		M14B	14.6	(R4E)		Lower Hand to Desk
		RL1	2.0			
		Total TMU's =	120.8	(or 0.0725 Minutes/Unit)		

FIGURE 5.1.2 Sample MTM analysis.

WORK FACTOR (WF) SYSTEM

The first predetermined time system was developed around 1925 by A. B. Segur, one of the first to recognize the association between motion and time. He formulated the principle, that, within allowances for normal variation, the time required by experts to perform a fundamental motion is consistent. He believed that work factors could be used to set standards for all manual and mental work. Segur developed *methods time analysis,* which could be used to analyze manual and manual/machine operations. Segur emphasized that the time required for

MEASUREMENT OF WORK

work depended on how the work was done and stressed that a complete description of the work performed was necessary.

In the early 1930s, union workers in Philadelphia were dissatisfied with the quality of the stopwatch time standards set for their highly controlled incentive jobs. This protest led to one of the first published predetermined time systems, called *work factor* [16]. The work factor system makes it possible to determine the normal time for manual tasks by using motion time data.

The definition of *basic motion* is that which involves the least amount of difficulty or precision for any given distance and body member combination. Work factor is used as the index of additional time required over and above the basic times for motions involving manual control and weight or resistance. Four variables affect the time of manual motions in the work factor system:

1. Body member used
2. Distance moved (measured on a straight-line basis)
3. Degree of manual control required
4. Weight or resistance of body member used and sex of operator

The eight standard elements of work factor are transport, grasp, preposition, assemble, use, disassemble, mental process, and release.

BASIC MOTION TIME STUDY (BMT)

In 1951, the Canadian firm of Woods and Gordon made the first significant contribution to predetermined time system literature by a foreign source. The Canadians developed basic motion time study from systems already available. The major advantage of BMT is its brevity. It is best used for factory jobs that follow fairly rigid motion patterns. In BMT, a *basic motion* is defined as a single complete movement of a body member. A basic motion occurs every time a body member, being at rest, moves and comes to rest again. Basic motion time study takes the following five factors into consideration in determining times:

1. Distance moved
2. Visual attention needed to complete motion
3. Degree of precision required in grasping or positioning
4. Amount of force needed in handling weight
5. Simultaneous performance of two motions

The motions of BMT fall into one of three classifications:

Class A. Stopped without muscular control by impact with a solid object.

Class B. Stopped entirely by use of muscular control.

Class C. Stopped by use of muscular control both to control the slowdown and to end it in a grasping or placing action.

A force factor is recognized, because handling heavy objects or overcoming friction require added muscular effort.

MODAPTS

MODAPTS is a relatively easy-to-use predetermined time system. MODAPTS stands for *mod*ular *a*rrangement of *p*redetermined *t*ime *s*tandards.

> MODAPTS is an Australian-developed time system based on the premise that larger body sections take longer to move than smaller sections. For example, in this system it takes twice as long to move a hand as it does to move a finger. It takes three times as long to move the forearm as it does a finger, and it takes four times as long to move the whole arm outward. From this simple framework, MODAPTS has built an entire system of predetermined macro time standards [18].

Because it describes work in human rather than mechanical terms, it has many more potential applications than earlier work analysis systems. The application is integrated with desktop computer processing capabilities, which simplifies its use.

MODAPTS is a recognized industrial engineering technique, meeting all criteria of the U.S. Defense Department and Department of Labor for developing industrial standards. Performance times are based on the premise that motions will be carried out at the most energy-efficient speed.

MODAPTS is used to analyze all types of industrial, office, and materials-handling tasks. Data from MODAPTS studies are used for planning and scheduling, cost estimating and analysis, ergonomic evaluation of manual tasks, and the development of labor standards [19].

Examples of action-based predetermined time systems follow.

GENERAL SEWING DATA (GSD)

General sewing data (GSD) uses a specially developed database that was derived from MTM core data [20]. GSD was developed by Methods Workshop Limited of Lancashire, England. The originators recognized that most apparel (sewing) operations followed a well-defined and repeating sequence of operations:

1. Get parts.
2. Put parts together.
3. Sew parts together with various alignments and repositions.
4. Trim thread.
5. Put parts aside.

When combined with batching operations, most of the tasks for sewing have been defined. GSD permits the user to rapidly analyze methods and generate time standards based on those methods. The major categories of GSD are as follows:

Obtaining and matching part or parts. This includes matching and getting two parts together, matching and getting two parts separately, matching parts to foot, and matching and adding parts with either one or two hands.

Aligning and adjusting. This includes aligning or adjusting one or two parts, aligning and repositioning assembly under foot, and aligning or adjusting parts by sliding.

Forming shapes. This includes forming fold, forming crease in folded part, and forming unfold or layout.

Trimming and tool use. This includes cutting with scissors, cutting thread with fixed blade, and dechaining parts with scissors.

Asiding. This includes pushing away parts and putting parts aside with one or two hands.

Handling machine. This includes machine sewing and different stops within half an inch, using the machine handwheel to raise or lower the needle, and manipulating the machine lever to backtack at the beginning or end.

Getting and putting. This includes getting parts and putting parts under various conditions, such as the use of one or two hands, contact only, getting part from the other hand, and putting the part onto the stack.

In addition to these elements, additional MTM elements are incorporated (reaches, moves, sit, stand, etc.). Figure 5.1.3 shows the GSD motions and times. A sample analysis of a sewing operation is shown in Fig. 5.1.4.

GENERAL SEWING DATA
LICENSED DATA CARD

CATEGORIES	ELEMENTS	CODE	TMU
OBTAIN AND MATCH PART OR PARTS	MATCH AND GET TWO PARTS TOGETHER	MG2T	76
	MATCH AND GET TWO PARTS SEPARATELY	MG2S	107
	(MATCH) PART(S) TO FOOT	FOOT	38
	MATCH AND ADD PART WITH 1 HAND (EASY)	MAPE	50
	MATCH AND ADD PART WITH 1 HAND	MAP1	56
	MATCH AND ADD PART WITH 2 HANDS	MAP2	69
ALIGNING AND ADJUSTING	ALIGN OR ADJUST TWO PARTS	AM2P	61
	ALIGN OR ADJUST ONE PART	AJPT	43
	ALIGN AND REPOSITION ASSEMBLY UNDER FOOT	ARPN	75
	ALIGN OR ADJUST PART(S) BY SLIDING	APSH	24
FORMING SHAPES	FORM FOLD	FFLD	43
	FORM CREASE IN FOLDED PART	FCRS	28
	FORM UNFOLD OR LAYOUT	FUNF	23
TRIMMING AND TOOL USE	TRIM - CUT WITH SCISSORS (1ST)	TCUT	50
	TRIM - ADDITIONAL CUT WITH SCISSORS	TCAT	25
	TRIM - CUT THREAD WITH FIXED BLADE	TBLD	33
	TRIM - DECHAIN PARTS WITH SCISSORS	TDCH	49
ASIDING	ASIDE - PUSH AWAY (SLIDING)	APSH	24
	ASIDE - PART WITH 1 HAND	AS1H	23
	ASIDE - PART WITH 2 HANDS	AS2H	42
HANDLING MACHINE	MACHINE SEW ½ INCH - APPROXIMATE STOP	MS1A	17
	MACHINE SEW ½ INCH - ACCURATE STOP	MS1B	26
	MACHINE SEW ½ INCH - PRECISE STOP	MS1C	37
	MACHINE HANDWHEEL TO RAISE OR LOWER NEEDLE	MHDW	46
	MACHINE LEVER TO BACKTACK AT BEGINNING	MBTB	34
	MACHINE LEVER TO BACKTACK AT END	MBTE	37
GET AND PUT DATA	GET PART WITH ONE HAND (EASY)	GP1E	14
	GET PART WITH ONE HAND	GP1H	20
	GET PART WITH TWO HANDS	GP2H	33
	GET PART CONTACT ONLY	GPCO	9
	GET PART FROM OTHER HAND	GPOH	6
	GET PART BY ADJUSTING GRASP	GPAG	10
	PUT PART TO APPROXIMATE LOCATION	PPAL	10
	PUT PART TO OTHER HAND	PPOH	6
	PUT PART ONTO STACK	PPST	14
	PUT PART LOCATE ONCE	PPL1	27
	PUT PART LOCATE TWICE	PPL2	47
ADDITIONAL MTM ELEMENTS	FOOT OR SHORT LEG MOTION (AUTOMATIC DEVICES)	F	9
	PACE OR STEP TO MOVE BODY	P	18
	BEND (AND ARISE)	B	61
	BEND DOWN	BD	29
	ARISE FROM BENDING	AB	32
	SIT	SIT	35
	STAND	STD	44
	EYE ACTION (SIMPLE CHECKS [BINARY])	E	7
	CRANK	C	15
	REGRASP	R	6
	APPLY PRESSURE	A	14

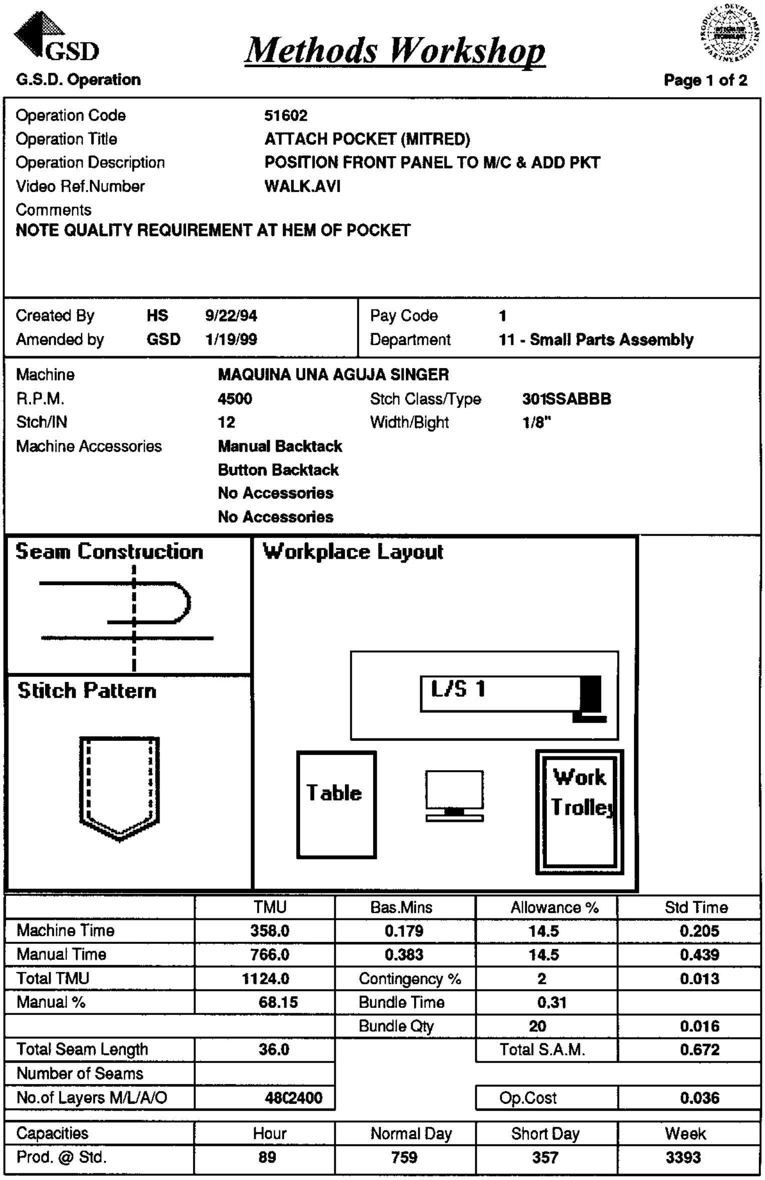
This data card is the property of METHODS WORKSHOP LIMITED. All rights and royalties within the General Sewing Data system have been retained by METHODS WORKSHOP LIMITED.

Do not attempt to use this card or apply method-time measurement in any way unless you understand the proper application of the data. This statement is included as a word of caution to prevent difficulties resulting from misapplication of the data.

FIGURE 5.1.3 GSD motions and times.

MTM-MEK

With the increasing emphasis on one-of-a-kind and small-lot production in the 1970s, the need for effective MTM work measurement in these areas became apparent [21]. Development of a predetermined time system to deal effectively with these areas presented unique problems as a result of the methods' variability of this type of work.


GSD
Seam Construction
Stitch Pattern
Workplace Layout
L/S 1
Table
Work Trolley

Methods Workshop

G.S.D. Operation

Page 1 of 2

Operation Code 51602
Operation Title ATTACH POCKET (MITRED)
Operation Description POSITION FRONT PANEL TO M/C & ADD PKT
Video Ref.Number WALK.AVI
Comments
NOTE QUALITY REQUIREMENT AT HEM OF POCKET

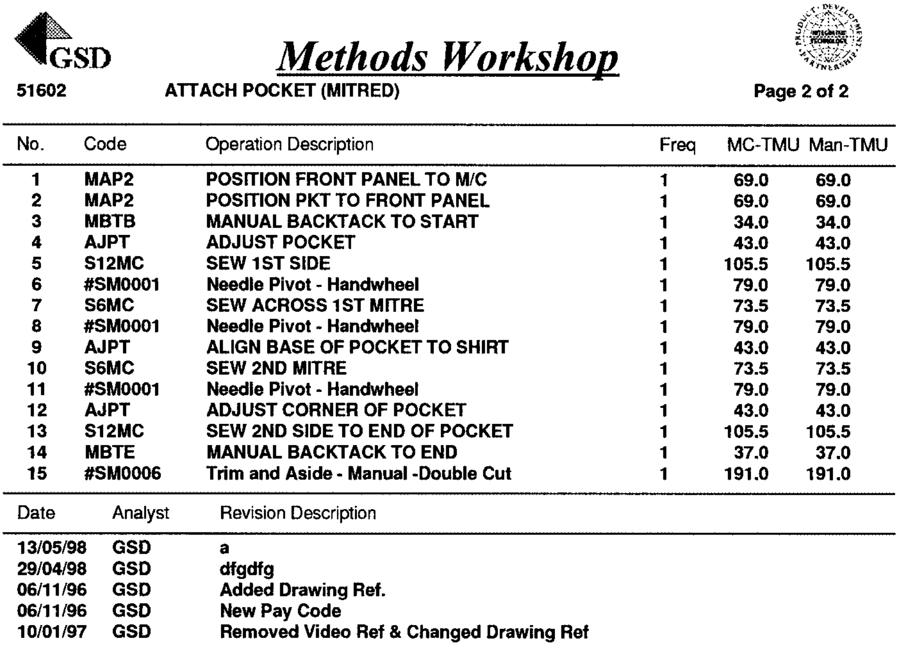
Created By	HS	9/22/94	Pay Code	1
Amended by	GSD	1/19/99	Department	11 - Small Parts Assembly

Machine	MAQUINA UNA AGUJA SINGER		
R.P.M.	4500	Stch Class/Type	301SSABBB
Stch/IN	12	Width/Bight	1/8"
Machine Accessories	Manual Backtack Button Backtack No Accessories No Accessories		

	TMU	Bas.Mins	Allowance %	Std Time
Machine Time	358.0	0.179	14.5	0.205
Manual Time	766.0	0.383	14.5	0.439
Total TMU	1124.0	Contingency %	2	0.013
Manual %	68.15	Bundle Time	0.31	
		Bundle Qty	20	0.016
Total Seam Length	36.0		Total S.A.M.	0.672
Number of Seams				
No.of Layers M/L/A/O	48C2400		Op.Cost	0.036

Capacities	Hour	Normal Day	Short Day	Week
Prod. @ Std.	89	759	357	3393

FIGURE 5.1.4 GSD analysis.



GSD

Methods Workshop

51602 ATTACH POCKET (MITRED) Page 2 of 2

No.	Code	Operation Description	Freq	MC-TMU	Man-TMU
1	MAP2	POSITION FRONT PANEL TO M/C	1	69.0	69.0
2	MAP2	POSITION PKT TO FRONT PANEL	1	69.0	69.0
3	MBTB	MANUAL BACKTACK TO START	1	34.0	34.0
4	AJPT	ADJUST POCKET	1	43.0	43.0
5	S12MC	SEW 1ST SIDE	1	105.5	105.5
6	#SM0001	Needle Pivot - Handwheel	1	79.0	79.0
7	S6MC	SEW ACROSS 1ST MITRE	1	73.5	73.5
8	#SM0001	Needle Pivot - Handwheel	1	79.0	79.0
9	AJPT	ALIGN BASE OF POCKET TO SHIRT	1	43.0	43.0
10	S6MC	SEW 2ND MITRE	1	73.5	73.5
11	#SM0001	Needle Pivot - Handwheel	1	79.0	79.0
12	AJPT	ADJUST CORNER OF POCKET	1	43.0	43.0
13	S12MC	SEW 2ND SIDE TO END OF POCKET	1	105.5	105.5
14	MBTE	MANUAL BACKTACK TO END	1	37.0	37.0
15	#SM0006	Trim and Aside - Manual -Double Cut	1	191.0	191.0

Date	Analyst	Revision Description
13/05/98	GSD	a
29/04/98	GSD	dfgdfg
06/11/96	GSD	Added Drawing Ref.
06/11/96	GSD	New Pay Code
10/01/97	GSD	Removed Video Ref & Changed Drawing Ref

FIGURE 5.1.4 GSD analysis. *(Continued)*

In response, the German MTM Association formed a consortium to develop an effective system for measuring highly variable work. The research and work was carried out by member companies of the German and Swiss MTM Associations and the Austrian MTM Group. The result was a data system developed for the specific needs of one-of-a-kind and small-lot production: the MTM-MEK data system.

In order to provide a system with the broadest range of application, only variables that could be readily identified in both the production and planning stages were utilized. Thus the MTM-MEK system can be readily applied in the preproduction stages of product development. The action elements were broken down in such a way as to ensure that they can be definitely recognized and clearly coordinated. Furthermore, a distinction was made between the activity and specific characteristics (e.g., handling of a construction part or handling of a tool). Additional variables are limited to those that can be identified from the external conditions surrounding the work process.

Analysis showed that one-of-a-kind production results in very complicated and complex motion sequences. At the same time, one-of-a-kind production rarely repeats the motion sequences with each repetition of the job. Without historical information or documentation of existing methods, the strategy for MTM-MEK uses the following:

- Variables affecting the elements are not derived from the motion sequence but rather from the peripheral conditions under which the motion sequence takes place.
- Therefore, the degree of complexity of a get-and-place sequence is not given, only that it takes place, how exact the place must be, over what distance the move takes place, and the weight or bulkiness of the objects.

This strategy results in the following consequences:

1. The total time applicable to a given operation can no longer be accounted for by a detailed method sequence prepared by an analyst, but rather must be statistically accounted for within the analyzing system.
2. The application of such analyzing systems requires that such a statistical match be determined in advance. The commonly used concepts of one-of-a-kind, batch, and mass production are much too vaguely defined for the purpose of determining the presence of this statistical match.

The utilization of statistical techniques to develop element times results in element classifications that are general in nature. Thus, the system contains no specific process or object-related data.

The development of data into general element classifications results in a minimum number of application elements. The small number of elements required results in quick access, which leads to high analyzing speed.

The MTM-MEK analyzing system uses the following element groups:

Get and place. Get one or more objects and place at a certain destination.

Handle tool. Get tool, apply tool, and place tool aside after use.

Place. Place one or more objects at a certain destination.

Operate. Operate control devices (levers, switches, handwheels, cranks, stops, etc.) that are attached to machines, appliances, and fixtures.

Motion cycles. At least two applications or movements of tools, levers, switches, or turning of cranks, repeated in succession. Also covered is the rotational portion of the turning of bolts by hand or with the fingers.

Body motions. Includes the elements walk, bend, and stoop as well as sit. Walk is analyzed as a separate element only if a distance of 2 m (80 inches) is exceeded. Bend and stoop are analyzed separately only if more than one of these occur within the elements get and place, place, and operate. Sit must always be analyzed if it occurs within a work process.

Visual control. Eye travel and inspection in independently occurring control or inspection operations. This includes the necessary eye travel to and from the place of inspection.

ANDARD DATA (USD)

Universal standard data is a modification of MTM-1. It was developed not only to supply specific time data that can be applied relatively quickly, but also to provide a concept of standard-data application.

> The basic concept of USD was formulated in 1954 when it became necessary to develop a large number of standards in a plant assembling a number of different models of farm tractors on a common progressive assembly line. The cycle time at each workstation was rather long, and there were a number of variations in the assembly procedures for each of the many different styles of tractors involved [22].

All of the USD motions are constructed from the basic MTM-1 data. The result is a shortcut method. The basic motions of USD are as follows:

Get object. Used for gaining possession or control of an object. The variables used include distance reached, the case of reach from MTM-1, and the case of grasp from MTM-1.

Place object (nominal weight). Used for placing, disposing, or positioning an object. It is based on the MTM-1 motions move, position, and release. The variables involved include the distance moved, the case of move, and the class of fit. Nominal weight is defined as 1 kg (2.5 pounds) or less.

Place object (significant weight). As with the place-object-nominal-weight motion, this is used for placing, disposing, or positioning an object based on move, position, and release. Additionally, it uses three weight ranges.

Get turn and place turn. This is a special case of get and place. It is used for motions that involve turning dials, knobs, and hand tools. It uses the MTM-1 motions grasp, turn, and release. The variables involved are the degrees of the turn and the force required to complete the turn. There are four categories for degrees turned and three categories for resistance or force.

Walk displacement. Involves a body turn and a walk to another location. It is based on the MTM-1 motions of turn body (case 1) and walk. The variables include the distance walked and whether there is any obstruction in the walk.

Miscellaneous body. This is a consolidation of the MTM-1 body, leg, and foot motions. It includes three classes of body displacement and individual foot and leg motion classifications.

Crank. Motion employed to turn a handwheel or crank. It is based on the MTM-1 cranking formula. Variables include the crank diameter, force required to operate the crank, and number of revolutions. There are two classifications for crank diameter, two classifications for required force, and 20 classifications for number of revolutions. Continuous cranking is also addressed with three classifications.

MSD

Master standard data (MSD) was developed by the Serge A. Birn Co. in the 1950s to set standard MTM-based data on manually controlled operations in which production was less than 100,000 units per year, or a few thousand units per week.

Between production runs, the operator would lose most of the skill he or she had developed. Statistically, a very high percentage of industrial work falls within this limited practice category. MSD was developed by statistically studying all motions. Because many motions studied occur rarely, they can be ignored [23]. The motions included in MSD are the most common MTM-1 motions: B, C, and D reaches. Also included are all grasps except G1C and nonsymmetrical positioning. Moves found in MSD are A, B, and C cases. The P1 and P2 positions are included, as are T . . . S turns, both releases, and apply pressures. Since MSD was developed for tasks that essentially have to be relearned, the likelihood of simultaneous motions is small. The exceptions are those motions that can be performed simultaneously without practice. MSD includes a simultaneous-motion chart along with tables for the following motions:

- Obtain
- Place
- Rotate
- Use
- Finger shift
- Body motions

MTM-2

MTM-2 is based on MTM-1. It consists of both basic MTM-1 motions and combinations of MTM-1 motions. According to the MTM Association for Standards and Research, MTM-2 was designed to fulfill the needs of practitioners who do not need the high precision of MTM-1 but where speed of analysis is important. Like MTM-1, it is useful for methods analysis, work measurement, and estimating. It was developed in Sweden [24].

There are nine elements in MTM-2. Just two of the nine elements have variable categories, which means that only 39 time values appear on the MTM-2 card.

Get. This is the motion with the predominant purpose of reaching for an object with the hand or fingers, grasping the object, and subsequently releasing it. Three variables influence the appropriate value. The case is determined by the nature of the grasping motions used. The distance reached is the actual path of travel. The third variable is the weight of the object being grasped.

Put. This is the motion used when the predominant purpose is to move an object to a destination with the hands or fingers. Three variables influence the appropriate value. The case is determined by the nature of the grasping motions used. The distance reached is the actual path of travel. The third variable is the weight of the object being grasped.

Apply pressure. This is used to describe the action of exerting muscular force on an object.

Regrasp. This describes the actions required when the purpose is to change the grasp on an object.

Eye action. This is used when focusing on an object or when shifting the field of vision to a different viewing area.

Crank. This is used when the fingers or hand move an object in a circular path of more than half a revolution.

Step. This applies to leg motions that are used to move the body or are longer than 30 cm (12 inches).

Foot motion. This describes a short foot or leg motion where the major purpose is not to transport the body.

Bend and arise. This applies to bending, stooping, or kneeling on one knee and the subsequent arise.

MTM-3 was also developed by the International Directorate. It is intended to be used where the product is manufactured in small batches and where the methods and motion distances can vary considerably from cycle to cycle. It is not appropriate for measuring highly repetitive work cycles [25]. MTM-3 has a total of only four motions, with only 10 time values specified.

Handle and *transport* are the first two motions. The cases are determined by the degree of control required and the distance moved. The other two motions are *step* and *bend and arise.*

An example of an activity-based predetermined time system follows.

BASICMOST®

BasicMOST® concentrates on the movement of objects [26]. Efficient, smooth, productive work is performed when the basic motion patterns are tactically arranged and smoothly choreographed. This provides the basis for the BasicMOST sequence models. The primary work units are no longer basic motions, but fundamental activities (collections of basic motions) dealing with moving objects. These activities are described in terms of subactivities fixed in sequence. In other words, to move an object, a standard sequence of events occurs.

Objects can be moved in only one of two ways: either they are picked up and moved freely through space or they are moved and maintain contact with another surface. The use of tools is analyzed through a separate activity sequence model that allows the analyst the opportunity to follow the movement of a hand tool through a standard sequence of events, which, in fact, is a combination of the two basic sequence models.

Consequently, only three activity sequences are needed for describing manual work [27]. The BasicMOST technique is made up of the following basic sequence models:

- The general move sequence (for the spatial movement of an object freely through the air)
- The controlled move sequence (for the movement of an object when it remains in contact with a surface or is following a controlled path during the movement)
- The tool use sequence (for the use of common hand tools)

1. *General move* is defined as moving objects manually from one location to another freely through the air. To account for the various ways in which a general move can occur, the activity sequence is made up of four subactivities:

A	Action distance (mainly horizontal)
B	Body motion (mainly vertical)
G	Gain control
P	Place

2. *Controlled move* sequence is used to cover such activities as operating a lever or crank, activating a button or switch, or simply sliding an object over a surface. In addition to the A, B, and G parameters from the general move sequence, the sequence model for controlled move contains the following subactivities:

M	Move controlled
X	Process time
I	Align

3. *Tool use* (equipment use) sequence covers the use of hand tools for such activities as fastening or loosening, cutting, cleaning, gauging, and writing. Also, certain activities requiring the use of the brain for mental processes can be classified as tool use. The tool use sequence model is a combination of general move and controlled move activities.

Figure 5.1.5 shows the sequence models comprising the BasicMOST techniques.

Whereas the three manual sequences comprise the BasicMOST technique, three other sequence models were designed to simplify the work measurement procedure for dealing with heavy objects.

Manual crane sequence covers the use of a manually traversed jib or monorail crane for moving heavier objects.

Powered crane sequence covers the use powered cranes, such as bridge cranes, for moving the heaviest objects.

Truck sequence covers the transportation of objects using riding or walking equipment such as a forklift, stacker, pallet lift, or hand truck.

Figure 5.1.6 shows the BasicMOST sequence models for equipment handling of objects.

BasicMOST is appropriate for any work that contains variations from one cycle to another. MiniMOST® should be used in situations in which a cycle is repeated identically over a long period of time, and MaxiMOST® should be used for nonrepetitive cycles longer than two minutes. For a further discussion of MOST work measurement systems please see Chap. 17.4.

MANUAL HANDLING

Activity	Sequence Model	Parameters
General Move	**ABGABPA**	A - Action Distance B - Body Motion G - Gain Control P - Place
Controlled Move	**ABGMXIA**	M - Move Controlled X - Process Time I - Align
Tool Use	**ABGABP ABPA**	F - Fasten L - Loosen C - Cut S - Surface Treat M - Measure R - Record T - Think

FIGURE 5.1.5 BasicMOST® sequence models.

EQUIPMENT HANDLING

Activity	Sequence Model	Parameters
Manual Type)	**ATKFVLVPTA**	A - Action Distance T - Transport Empty K - Hook Up And Unhook F - Free Object V - Vertical Move L - Loaded Move P - Place
Move With Powered Crane (Bridge Type)	**ATKTPTA**	A - Action Distance T - Transport K - Hook Up And Unhook P - Place
Move With Truck	**ASTLTLTA**	A - Action Distance S - Start And Park T - Transport L - Load Or Unload

FIGURE 5.1.6 BasicMOST® sequence models for equipment handling of objects.

SUMMARY AND FUTURE DIRECTIONS

Work measurement provides essential data for the management of all organizations. Many organizations will elect to use predetermined time systems to provide this information to assist with the management and operation of the organization. Industrial engineers should be skilled and knowledgeable in setting standards, regardless of the methodology used. Computers are used to assist in the compilation of the standards. Competently trained and educated individuals will be required to use the automated systems.

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BIOGRAPHY

Larry Aft, P.E., has been a professor in the Industrial Engineering Technology Department of Southern Polytechnic State University in Marietta, Georgia, since 1971. While in that position, he has consulted with over 100 organizations on productivity and quality-related issues. A senior member of IIE, he has served on the Board of Directors for the Society for Work Science. He received the Institute's Phil Carroll Award in 1998. He is also a Fellow of the American Society for Quality. His publications include *Productivity, Measurement and Improvement, Wage and Salary Administration,* and *Fundamentals of Industrial Quality Control.* He holds industrial engineering degrees from Bradley University and the University of Illinois.

CHAPTER 5.2

PURPOSE AND JUSTIFICATION OF ENGINEERED LABOR STANDARDS

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> *We can see and feel the waste of material things. Awkward, inefficient, or ill-directed movements of men, however, leave nothing visible or tangible behind them.*
>
> Frederick Winslow Taylor

Engineered labor standards are a cornerstone of industrial engineering. Through the years, many books and articles have been written on the application of the many techniques that make up the science of work measurement, though very few have actually discussed in detail the benefits of engineered labor standards. Over the years, work measurement has lost some of its popularity, mostly because the industrial engineering community has failed to outline the overall benefits associated with a well-tailored work measurement program.

This chapter will discuss the purpose of engineered labor standards, justify their implementation, and outline why work measurement is so crucial to the business decision process and how it becomes impossible to optimize any operation without it. The notion of engineered labor standards as an old approach developed at the beginning of the twentieth century to make people work harder will be debunked. The global benefits of implementing engineered labor standards will be revealed, and in the end, the reader will discover that work measurement is a complex information system that provides timely and accurate measurement of the work content of a task, process, and operation—information that is crucial to so many day-to-day managerial tasks.

INTRODUCTION

Germane to this discussion are Frederick Taylor's thoughts at the beginning of the twentieth century as he was laying the foundations of scientific management, the precursor to industrial engineering. At the beginning of the twenty-first century, industrial engineers around the world are working hard to reduce operating costs and optimize processes. The industrial engineering profession has seen many changes during the last hundred years, but one fact still remains the same: identifying and eliminating wasted time without the proper tools remains at best an elusive process. Looking back at the early days of industrial engineering, we recognize a group of exceptional individuals—Frederick Taylor, Frank and Lillian Gilbreth, Henry Gantt, and others—who dedicated a good part of their lives to a quest to develop better and more efficient companies. These individuals fought hard to defend what they believed was the road to greater prosperity for both employers and employees. Along the way they invented, refined, and tailored fundamental tools needed to wage the ongoing battle toward better efficiency. Work measurement is considered one of their finest achievements, which may explain why many consider it the forerunner of industrial engineering. These pillars of our profession have left us a legacy that should be preserved and enhanced to benefit society as a whole.

Most industrial engineers dedicate the early part of their careers to learning the basic requirements of their future profession. They typically spend three to five years in universities or colleges cultivating the core knowledge of industrial engineering. Their diplomas attest that they have been exposed to a wide array of complex tools. Unfortunately, over the years universities have modified their vision of what the content of our toolbox should be. The industrial engineering community's minimal reaction to these modifications of the curriculum have been leading work measurement and other important basic tools down the path to eradication. Very few recent graduates can recognize and explain the benefits of engineered labor standards. An even smaller number would be able to prescribe engineered labor standards solid enough to withstand the most basic of union audits. Some very serious questions arise: Can this new breed of industrial engineers be true to the goals set forth by the pioneers of our profession? Will future generations of industrial engineers be a source of sustainable savings? Will industrial engineering lose its particular identity and become part of the melting pot of management consultants? To salvage the industrial engineering profession, it is imperative that we supplement the institutionalized training of our industrial engineers with an apprenticeship in the true cost-saving tools.

This chapter outlines the major reasons for using work measurement. The reader who is less familiar with work measurement will find in this section an understanding of the critical role that engineered labor standards play in a well-organized operation. Readers more familiar with the concept of work measurement will find the answer to the following question: When should you reach down in your industrial engineering toolbox and pull out your work measurement knowledge to build engineered labor standards?

The goals of this chapter are to help every reader recognize that the added value in using engineered labor standards resides in the fact that it will enable you to make an informed decision rather than relying on assumptions or luck. This discussion will also help the reader sell the concepts of work measurement and engineered labor standards.

Let us start by tackling the seemingly simple tasks of accomplishing our day-to-day activities. Life is a constant struggle to meet time commitments and deadlines. We are incessantly dealing with time constraints (driving to work, writing a proposal, performing an engineering task, etc.) that on most occasions we struggle to meet. Sometimes we would like to believe that we are just prone to bad luck, but in reality our planning processes are deeply flawed. From our personal experiences we should come to realize that using time estimates to plan our daily lives is at best barely adequate. And even though estimates might suffice to run many of our daily activities, is that the way to make business decisions? Before answering this question, remember that in business the saying that "time is money" always holds true. Therefore, it would be surprising to find many individuals who would want to invest in companies that ignore the importance of time-related information.

In the new millennium, some are questioning the usefulness of engineered labor standards. They are rejecting the usefulness of a 100-year-old technique. They contend that such traditional techniques have very limited use compared to newer, high-tech solutions. In the next pages, we will show that today's global economy actually accentuates the need for work measurement. This context of global competition will force every company to excel in every aspect of their business, which includes controlling labor costs. The need for higher productivity has reached new heights; it started out as a means of generating higher profits and has developed into a question of survival. Making important business decisions based on assumptions is just too risky. It is like landing a plane in thick fog without instruments. You might manage it if it is your lucky day. You may choose to rely on either luck or solid industrial engineering solutions to securely build the foundation of your business, but in the end there is only one right choice.

This chapter demonstrates how engineered labor standards can help every industrial engineer fulfill his or her most important duty, which is to be a highly cost-effective employee. We must come to grips with the notion that the only good IE is one who generates sustainable savings.

WHO BENEFITS FROM ENGINEERED LABOR STANDARDS?

The general perception is that engineered labor standards will benefit only management. Many employees and unions look upon standards as just another way management has devised to exploit the labor force. In fact, engineered labor standards benefit society collectively by quantifying the expectation linked to a fair day's work. It touches every facet of running a business and thus directly affects the costs of producing goods and services. Engineered labor standards provide management with a scientific approach to measure work and set the company's expectations. By the same token, they enable employees to verify and validate the company's numbers. Employees can clearly understand the required level of productivity. Properly implemented engineered labor standards will alleviate anxiety because employees will always know what is expected of them.

The implementation process plays a crucial role in assuring the recognition and acceptance of engineered labor standards. To reap the full benefits, educating both management and workers on the concept of engineered labor standards has to be firmly entrenched in the implementation process. Adhering to this approach will enable the implementation team to demystify the notions associated with engineered labor standards. Management will gain a better understanding of the role that engineered labor standards can play to improve their ability to manage effectively. Employees will find a forum to voice their concerns and to receive explanations on the engineering process behind the labor standards. Through education, both management and unions will understand that standards are fair and equitable for both parties. By demystifying work measurement, we will remove the hurdle of fear that prevents management and employees from fully appreciating the purpose of engineered labor standards.

WHICH SECTORS BENEFIT FROM ENGINEERED LABOR STANDARDS?

There is a misconception that engineered labor standards can be implemented only in manufacturing operations. This is based mostly on historical trends showing that the bulk of our past engineering efforts implemented engineered labor standards in the dominant manufacturing sectors of the time. In reality, there is no reason to limit the scope of work measurement exclusively to this sector. Instead, any task for which we have a production unit that can be physically quantified is a potential candidate. With no boundaries imposed by the actual sector, we can concentrate on defining the payback of each case to decide if we are dealing with a feasible labor standard project. It is then a simple question of basic cost analysis. We will proceed with the development of nontraditional labor standards any time the savings outweigh the amount of effort needed to build the standard. By not limiting ourselves to the traditional applications of engineered labor standards but rather expending its usage to areas and sectors that need to be improved, we will broaden the recognition of work measurement as a useful cost-saving process. For example, many consider indirect costs as part of the inconvenience of running a business. They do not recognize that we can accurately measure and reduce them. In fact, a large part of the indirect labor costs associated with manufacturing can be decreased by introducing labor standards on tasks such as janitorial functions, clerical work, and set up times. Standards can also have tremendous impact on other sectors such as the service industry. Any operation needs to be visualized as a series of processes. Work measurement can then be used to improve these processes, resulting in more efficient and cost-effective production of goods and services. So far, engineered labor standards have played a minor role within the service industry—with some very unfortunate consequences. The public sector of many governments is but one example of our inability to tap into that market. In most industrial countries, the largest service provider happens to be the government, which in many cases is also one of the best examples of inefficiency, cost overruns, and mismanagement. As we start to perceive these institutions as nothing but huge “service-manufacturing plants,” we will recognize the usefulness of engineered labor standards in streamlining their operations.

The benefits associated with engineered labor standards that are discussed in the rest of this chapter apply to the entire supply chain—both the direct and the indirect labor contents. Thanks to its flexibility, work measurement becomes a universal practice that may be applied to a wide spectrum of tasks and industries with equally impressive results.

GENERAL PURPOSE OF ENGINEERED LABOR STANDARDS

Any decision we make is greatly affected by the quality and quantity of information at our disposal. Numerous management decisions directly affect the future of a company as well as the livelihood of its employees. With such important consequences at stake, it is imperative that the decision process be based on sound information. Clearly, the probability of making the proper decision rises as our knowledge increases. Using assumptions instead of factual information greatly reduces the quality of our decision-making process. When dealing with time-based information, the use of engineered labor standards provides management with the most reliable information and eliminates the need for estimates and educated guesses. The forte of engineered labor standards lies in its ability to consistently provide us with solid and accurate information.

It is hard to think of any production-related decision that is not dependent on the knowledge of time, but for now we will limit ourselves to four critical management tasks that necessitate a profound knowledge of time: planning, cost control, productivity measurement, and goal setting. Using a work measurement strategy to ensure an optimized process can accomplish these four crucial tasks. By taking away the guesswork in production decisions, engineered labor standards give management the credibility it needs to become effective.

SPECIFIC REASONS FOR USING ENGINEERED LABOR STANDARDS

A century of evolution has turned work measurement into a powerful and flexible tool. Not only have we refined the early techniques such as stopwatch time study, but we have also added newer and more powerful methods to fulfill the growing needs of the industry. Over the years, the advent of affordable computers has provided the industrial engineer with the means to develop more productive and flexible labor standards tools. At the same time, the industrial engineering community has worked hard to refine the standards engineering process to better accommodate the ever-changing constraints imposed by labor/management relations. Today’s industrial engineers have access to superior work measurement tools that promote new uses for engineered labor standards in both traditional and nontraditional applications. Despite this tremendous evolution of our capabilities to accurately build engineered labor standards, a very puzzling fact remains: Why do some companies still rely on nonscientific measurement to manage their daily operations? By ignoring the wide array of work measurement tools available and relying on estimates and historical data, these companies jeopardize their existence and the well-being of their employees. We can only conclude that even though the industrial engineering profession has succeeded in developing the science of engineered labor standards, it has failed miserably in selling this concept to management.

The fact that even today many people refer to work measurement as "time and motion study" is a testament to our failure to modernize the concept of measuring time. Unfortunately, most of these people also assume that labor control is the sole purpose of labor standards. Considering the true scope of work measurement, this constitutes a very myopic view of the actual potential of engineered labor standards. The ability to tap work measurement's full potential is linked to our ability to recognize and sell the multiple benefits of engineered labor standards. In selling engineered labor standards to both management and unions, we must be ready to give an unequivocal answer to the following question: "What's in it for us?" Failure to do so may deny these companies the opportunity to greatly improve their competitiveness while preserving a fair work environment. On the other hand, providing the right answer elevates work measurement to the level of recognition that it deserves. So let us find out: "What is in it for everyone?"

Optimizing the Methods Engineering Process

The first steps of any engineered labor standard implementation are to initiate a global review of the current work process. The target of this review will be the inefficiencies inherent in the current process. The initial savings associated with the first step of this process will be used to fuel additional savings that will in turn create even more opportunities to save, creating a sort of chain reaction of savings. To achieve such results, it is important to include *methods engineering* in the first step of the engineered labor standard program. This combination of methods engineering and work measurement becomes an extremely potent tool in eradicating unproductiveness, as it attacks both the technical and psychological nature of the inefficiencies. The elimination of wasted time and effort will always remain an essential attribute of engineered labor standards projects. Any engineered labor standards implementation should be regarded as a golden opportunity, not only to quantify our processes, but also to improve their efficiency.

Traditionally, work measurement has been the second step of the work study process. Adhering to this method, an industrial engineer would first apply methods engineering to improve the task, then resort to work measurement to measure the newly modified process. Since it is common to discover additional improvements during the work measurement phase, using a linear approach falls short of realizing the true potential of work study.

This modifies our perspective of the traditional relationship between methods engineering and work measurement. We can no longer view methods engineering as a simple prerequisite to work measurement. By the same token, it is dangerous to think of methods engineering as a stand-alone process by which we can improve productivity. Experience has shown that it is one thing to identify potential savings and yet another to reap the benefits. Work measurement is the mechanism by which accountability is added to the methods engineering phase to ensure that any identified savings will make it to the bank. (See Fig. 5.2.1.)

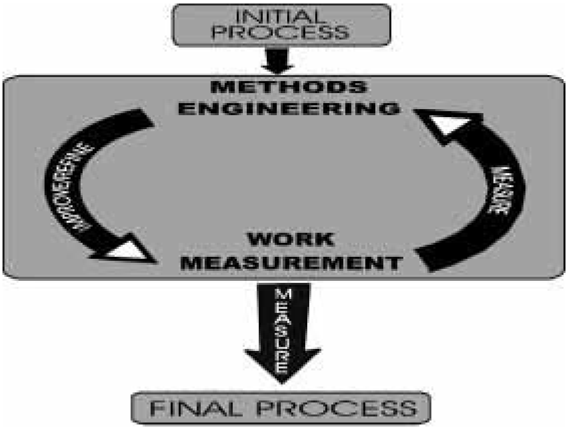

FIGURE 5.2.1 Symbiotic relationship between methods engineering and work measurement.

We are in essence defining the existence of a symbiotic relationship between methods engineering and work measurement. These two processes work in tandem, not only by completing each other, but also by maximizing their individual and collective yields. The necessity to improve a task before measuring it has to become intuitive to every industrial engineer. It would be falling short of our goals if, as industrial engineers, we were satisfied to implement engineered labor standards on improperly designed methods. By the same token, it should be logical for us to recognize that the only way to harvest the true potential of methods engineering is to implement engineered labor standards. This will enable upper management to hold people accountable for the identified savings. With such a process in place, companies will be guaranteed to benefit from the savings generated by their methods engineering process.

Quantifying the Potential of Our Current Process

It is the duty of management to ensure that their company is always striving to improve its situation. In the 1990s, most companies seized an opportunity to motivate their personnel and reassure their clients by coming up with a mission statement. Most of these statements convey a feel-good message of what the company wants to offer its clients. We are living in a fantasy world if we believe in the fallacy that it is sufficient to know where we want to go in order to get there. Even if it were that simple, a key component of planning a path to our ultimate goal starts with knowing where we currently stand. As in finding directions on a map, you need to know both your destination *and* your origin in order to get from here to there.

The same applies to decisions regarding the implementation of new processes. It is imperative to know the potential of our current process in order to avoid two serious and costly situations:

- Without knowing it, our company is an underachiever.
- Even though we invest in new processes that seem justifiable under the current situation, we never see any real payback.

All companies aspire to become more efficient. In their search for improved efficiency, they are often tempted to look for miracle cures that promise drastic improvements in their processes. This tendency for quick-fix solutions led us into the buzzword era of the 1990s. On some occasions, positive results will issue from a buzzword project, but at what cost? Industrial engineers should not relegate themselves to the role of buzzword salespeople, content to sell the flavor-of-the-month fix instead of implementing durable engineering solutions.

If industrial engineers are to implement durable solutions, they must assess the capability of the current processes before deciding on any major capital investment. It is crucial to know if we are getting the maximum out of our current process. It is a common error for management to compare the theoretical output of a potential solution with the current throughput of present processes. The evaluated payback of such a comparison will always overstate the potential of the envisioned process. For such an analysis to be fair and valid, we must know the potential of our current processes. (See Fig. 5.2.2.)

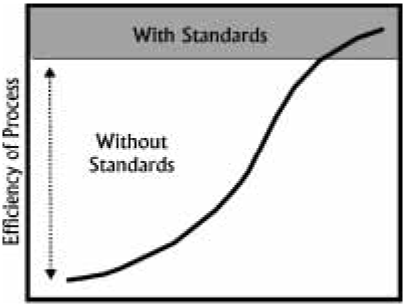

FIGURE 5.2.2 Understanding the total potential of a process.

An engineered labor standard is the means by which it is possible to accurately determine the potential of current processes. This in turn sets a precise benchmark to which new alternatives may be objectively compared. By following this structured methodology, every possible alternative will be correctly evaluated, thus eliminating the risks of investing in costly yet inferior solutions.

Calculating the true potential of our current processes also helps to put into perspective improvement projects sought by management and consultants. Too often, management and consultants erroneously claim they have achieved tremendous gains over the current process through the implementation of new technology or the application of new methods. It is hard to refute the fact that improving a process is good, but these claims need to be compared to the full potential offered by the current process. It then becomes a question of assessing whether the new solution truly represents an attractive payback. Did we get our money's worth? For example, picture a simple manual process where the workers are performing well below the standards level. Say they are producing at an average rate of 100 units per hour. Through the purchase of new equipment, the production rate climbs to 130 units per hour. The fact that we realize a 30 percent increase does not necessarily mean that we have implemented a solution that provides a superior yield. In this case, a work measurement study later revealed that the initial process could have yielded 150 units per hour through the implementation of labor standards. By ignoring the potential of the initial process, we were falsely led to believe that we had achieved tremendous gains when in fact we had simply failed to maximize the initial process. The use of engineered labor standards would have prevented an unnecessary capital expenditure while at the same time providing the company with a higher production rate.

Setting Fair and Realistic Labor Expectations

The talk of quotas and labor expectations has been known to stir up some of the most polarized and vocal discussions between employees and management. This emanates from the fact that everybody has a subjective notion of a fair day's work. On one side, workers often feel exploited, believing they are giving more than they are getting paid for. On the other side, managers feel they are not getting their fair share of the work they are paying for. In the end, everybody involved will be held accountable to certain expectations, obtained through different methods.

- Using an informal number set or imposed by one of the parties
- Negotiating a number between the parties
- Using historical data to extrapolate a number
- Estimating (guessing) a number that seems realistic
- Using work measurement to build engineered labor standards

We need to choose between four nonscientific methods and one scientific approach. The use of nonscientific or informal strategies to set expectations will always be prejudicial to one of the two parties. Furthermore, these expectations are often inconsistent, thus creating a climate of uncertainty and distrust. These expectations will always be much lower than engineered labor standards, and this translates into lost opportunities for companies, including an accompanying ripple effect. It is not uncommon to see labor productivity go up by anywhere from 15 to 100 percent following the implementation of engineered labor standards.

With this in mind, industrial engineers must be careful never to equate expectations with engineered labor standards. Only by using work measurement to build engineered labor standards can a fair and realistic productivity measurement be obtained. When properly done, work measurement will generate productivity measurements that are not only accurate but, most important of all, fair and defendable. With a properly designed work measurement program, the engineered labor standards will be well maintained, ensuring that the productivity measurement stays accurate over time. The scientific foundation of work measurement gives it legitimacy in the eyes of both unions and management. By combining a proper education program with the intrinsic legitimacy of work measurement, it becomes easier to get acceptance from both parties. Once the productivity measurements are accepted by both parties, they will be able to concentrate their time and energy on further improving the processes and increasing the competitiveness of the company.

It is important to emphasize the defensible nature of engineered labor standards. In most cases, a simple union audit will suffice to reassure the union and its membership of the validity of the measurement. Should it become necessary to go into arbitration, work measurement is the only system you can count on.

Prerequisite to Wage Incentive Systems

As companies seek avenues to reduce costs, there is a resurgence of wage incentive programs. Some differ vastly with those of the past, but many still rely heavily on the performance of the worker or workers as a major component of the incentive calculation. Many companies see these systems as a way to get additional output without spending on capital investment. For some, the quick potential of these systems lures them into a dangerous trap. These companies will implement incentives before using engineered labor standards to ascertain their current process and future potential. To clearly illustrate why this becomes a trap, we need to clarify the goals behind incentive programs. The purpose of incentives is to achieve levels of productivity above and beyond those dictated by engineered labor standards in exchange for some sort of payment (money, time off, stocks, etc.). The logic behind these programs is that you are willing to trade potentially higher direct labor costs for greater reduction in your indirect costs.

The steps toward successfully implementing an incentive should be as follows: apply methods engineering to the task at hand; build engineered labor standards; and finally, put the incentive program in place. When these logical steps are not performed in sequence, the company will begin to pay incentive rates well before it benefits from increased performance levels. Another deception occurs as companies invariably interpret any increase in productivity to be entirely due to the incentive program. Most companies believe that their incentive system works and are happy with the final results. This situation may last forever if the workers do not get too greedy by performing consistently at very high levels of performance. If and when the company identifies problems with the incentive program, it will face three difficult alternatives to correct the situation.

- Keep paying incentives for non-incentive-level performances.
- Negotiate with the workers to buy back the incentive program. This is usually done through an increase in the base pay.
- Implement engineered labor standards and modify the incentive program to conform to a normal performance level and deal with the grievances.

The first two alternatives do not make a lot of business sense, and the third one represents a huge battle with the employees and/or their union. This situation could have been avoided if the company had simply chosen to implement engineered labor standards prior to starting the incentive program. Only by accurately identifying the level of incentive performance will a company truly capitalize from any incentive program.

Avoiding Unnecessary Capital Investment

By now it should no longer be a secret that the use of engineered labor standards helps a company make more efficient use of its labor force. What is not as intuitive is that by optimizing its labor force, a company will also improve its utilization of other resources. Only by fully understanding the global impact of labor standards can we appreciate their overall potential. We should always assess the costs of providing the necessary tools, equipment, and facilities for each employee. The tool and equipment costs will be proportional to either the total number of workers or to the number of workers on a given shift. The costs associated with the facility (work, parking, locker, and cafeteria space) are either incremental or linked to the number of workers on the busiest shift. As a company adds workers to its peak shift, it will need to invest considerable capital to support its workers.

To a growing company, the impact of engineered labor standards can be phenomenal. The company will be able to sustain its growth strategy without draining its capital. It is not uncommon for a company to be able to absorb a 15 to 30 percent increase of its volume simply by implementing engineered labor standards.

The impact that engineered labor standards have on capital investment costs needs to be carefully evaluated on a case-by-case basis to accurately reflect the inherent costs of the particular operations.

The distribution and warehousing sectors are prime examples of operations that fully benefit from engineered labor standards with respect to avoiding capital expenditures. To accomplish his or her task, each worker on a given shift requires either a pallet jack or a forklift. Considering that the acquisition cost for this type of equipment varies from $5000 to over $100,000 per unit, it is quite easy to see that optimizing our labor force has a major impact on reducing capital investment costs.

Reducing Overall Operational Costs

One of the most noticeable effects of implementing engineered labor standards is increased productivity of our touch labor workforce. To thoroughly understand the impact of the implementation, we must fully grasp the various operational costs that are reduced. The three major sectors affected are direct labor, indirect labor, and operating costs.

Reducing Direct Labor Costs. When people think about the impact of engineered labor standards, the first thing that often comes to mind is the impact they have on reducing direct labor costs. This relationship between engineered labor standards and direct labor cost savings is so strong that it has, unfortunately, come to overshadow many of the other direct benefits. This perception makes it more difficult to sell the overall benefits of work measurement to workers and unions. Why do people tend to limit the scope of work measurement to only its impact on direct cost? There exists a very simple answer: the results of the implementation on direct labor costs are usually so dramatic that management is overwhelmed by the savings and does not look further to appreciate the full potential at hand.

Even though we are familiar with the impact of implementing engineered labor standards, it remains difficult to predict the average direct labor savings. On the other hand, we can derive from experience a benchmark of what to expect. It is common to achieve direct labor cost reductions in the range of 15 to 100 percent. These figures will fluctuate according to the preimplementation level of productivity. The following factors play a key role in assessing the opportunity associated with the implementation of engineered labor standards: nature of the task, level of automation, quality of supervision, turnover rate of the labor force, repetitiveness of the task, union/management relation, and others.

Reducing Indirect Labor Costs. For some indirect functions, there exists a direct link between the number of workers needed to execute these tasks and the number of workers executing direct work. Under these conditions, a reduction in the size of the direct workforce will translate into a reduction of the indirect labor. The indirect workers most affected by a reduction of the direct labor are the support and supervision staff. Here again, it is difficult to generalize and come up with universal guidelines. The best way to illustrate the impact of engineered labor standards on the size of the indirect workforce is to examine a very common situation.

As companies go through their growth phase, increasing sales and volume create capacity problems. To avoid huge capital expenditures, many companies will solve capacity problems by adding additional shifts. The indirect costs associated with this solution are evident: the company will need to hire new indirect staff to cover supervision and support (janitors, clerks, etc.) duties. An increase in the output of the direct labor force through engineered labor standards will avoid or delay the need for an additional shift and thus avoid substantial costs and inconvenience associated with recruiting and hiring extra staff.

Reducing Operating Costs. Earlier in this chapter, we explained how engineered labor standards can help a company avoid unnecessary capital expenditures. By the same token, engineered labor standards will enable a company to reduce its operating costs. This reduction is directly linked to the efficiency improvement associated with the direct and indirect labor force.

The implementation of engineered labor standards will shorten the total cycle time associated with a task. The impact of engineered labor standards on operating costs will be greater on operations that include machine and/or process times. We can be assured that the manual component of the cycle time will be greatly reduced following the implementation of the engineered labor standards. To a lesser extent, there should also be a reduction of the time associated with the machine and/or process component of the cycle. Let us examine how a decrease in either the manual or machine/process time contributes to lowering the operating cost.

By reducing the manual component, we will be able to run more cycles within the same time period. This translates into a higher utilization rate for our equipment. In the case of machine/process times that have high idle costs, such as furnaces and blast freezers, this will translate into important savings.

The savings associated with a reduction of the machine/process component are straightforward to calculate. In that case, the actual running costs of the machine or process is the variable to watch for.

Recognizing the potential of engineered labor standards in dealing with machine/process-oriented tasks opens new possibilities for work measurement. Many engineers are unable to justify work measurement projects when dealing with these types of tasks because they base the entire payback calculation on the direct labor savings while totally ignoring the reduction in operating costs. Industrial engineers are wasting tremendous opportunities to generate huge savings considering that, for many processes, the operating costs are several times higher than the hourly wage of the operator.

Supporting Supervision and Labor Control Functions

An effective group of supervisors is a key element to running an efficient operation. Supervisors are the primary link in the pipeline that feeds information up and down between the floor employees and upper management. One of their principal roles is to ensure on a daily basis that every employee performs to a satisfactory level of productivity. Despite this important responsibility, many supervisors choose to spend much of their time in the office; they seem to want to avoid interaction with the employees. What pushes a supervisor to become invisible? In analyzing this behavior, two main reasons come to mind: that the individual is simply not suitable for a supervisory role or that upper management is not providing supervisors with the proper tools to accomplish their tasks. Supervisors who are not confident in their capabilities will never be respected by their employees, which means they will never be able to fully accomplish their duties.

Most supervisors consider addressing an employee's inadequate productivity as one of the more difficult tasks to do. Many supervisors will simply choose to ignore this problem. By providing engineered labor standards to the supervisors, the company gives them an effective tool to deal with the issue of low productivity, enabling them to accurately pinpoint employees who are experiencing difficulties in reaching the required performance levels. They can then trigger appropriate mechanisms to rectify the situation.

In the event that a given situation degenerates to a point that requires disciplinary measures, the supervisor will feel confident knowing that engineered labor standards are a proven and reliable measurement, especially if the matter has to go into arbitration. Engineered labor standards legitimize this difficult aspect of supervision. The employees will not have any choice but to recognize that the supervisor's decisions are fair and above favoritism, which goes a long way in establishing the credibility of the supervisor.

PURPOSE AND JUSTIFICATION OF ENGINEERED LABOR STANDARDS

Supporting Basic Managerial Functions

As was initially discussed, many management decisions use time as an input. The strength of these decisions will be directly linked to the quality of the time measurement. Since work measurement is the most accurate way of calculating these times, it is crucial to outline some common managerial tasks that can be better accomplished by using information from the engineered labor standard system.

Scheduling Resources. Efficient resource scheduling is a sign of a well-tuned operation. Inefficient scheduling practices result in wasted resources, excessive inventories, late deliveries, and many other problems that display a lack of control over the operation. For most operations the scheduling process should be fairly simple. It involves having knowledge of two simple internal processes. First, there is a need for thorough knowledge of the different processes involved and how they interact with each other. Second, the exact length of these processes needs to be identified in order to synchronize and coordinate them. Why do we have so much difficulty properly scheduling our resources? On most occasions, a schedule is created without using accurate information. Realizing that quality information is not available, most people turn to an informal method to gather their own information. This method usually jumps to conclusions too quickly and eventually falls short of the anticipated results.

To illustrate the shortcomings of using inaccurate information, we will examine the case of a metal-stamping department. The operators were spending much of the workday idle, waiting for racks of raw material to be brought to them or waiting for racks of processed parts to be taken away. At any given moment, dozens of heavy presses were idle. The cost of having equipment worth millions of dollars idle, not to mention highly skilled personnel waiting for work, became unbearable to the upper management. Relying on a quick assessment of the problem, the managers came to the conclusion that this situation was caused by a shortage of material handlers. They promptly increased the number of forklifts and were baffled by the results: the problem got worse, not better. They had failed to recognize that they were facing a scheduling problem. The information used for scheduling was based on historical data. The person in charge of scheduling knew that these figures were unreliable and decided to apply his own "correction factor" to the times. The net result was an overallocation of resources that created bottlenecks in the operation, increased the amount of work in process, and consequently caused delays to many of the workstations. The scheduling process had failed simply because the proper operation times were missing. Once engineered labor standards were implemented, the scheduling process became dependable, and the informal system was thrown out the window. This brought the delays under control and increased the throughput.

Cost Control. The golden rule of running a business is very simple: just minimize the expenses, maximize the revenues, and the business automatically will maximize its profits. Many will say that this is easier said than done, but with the right productivity measurement, this goal is much easier to achieve. To be effective in controlling our expenses, we must be able to quantify the different components that make up the total cost of our product or service. Engineered labor standards play a crucial role not only in controlling the labor costs, but also in minimizing them. One can argue that you do not need engineered labor standards to know your labor costs, and this is true to the extent that you are only concerned with suboptimized costs. The strength of engineered labor standards lies in providing an accurate measurement of the reasonable costs associated to a given product or service.

The ability of a company to manage within its budgeted costs is the most important step in controlling costs. Engineered labor standards' greatest impact is its ability to set accurate measurement by which management can establish realistic production costs and then hold the employees accountable. This accountability spans over many levels of the company, from the workers performing the task to the supervisors managing the operations and all the way up to the individuals responsible for planning and scheduling. With a measurement system that reflects current conditions, it becomes difficult for individuals to find valid excuses for not achieving the objectives.

The emergence of activity-based costing (ABC) reflects this necessity that companies have to truly understand the cost structure of their products. The implementation of engineered labor standards is an important prerequisite to structuring an effective activity-based costing strategy. The breakdown of operations and processes essential to building accurate engineered labor standards provides a wealth of information about the components of the total cost. Using this detail makes it possible to develop the appropriate cost structure. An added benefit of the engineered labor standards process is its ability to clarify the borders between indirect and direct costs. Many costs that were calculated as indirect costs can, through this process, be directly attributed to specific products or services. This real distribution of costs is particularly evident when defining standards that involve setup times, material-handling personnel, janitorial tasks, and other similar situations. The company's newly acquired knowledge about the real cost structure of its product line will enable it to better focus on improving its bottom line.

Pricing. To formulate a successful product or service (i.e., one that generates profits), it is necessary to come up with a pricing strategy during the first steps of the development phase. The pricing strategy should become a logical extension of the company's cost-estimating and cost-control functions. The use of engineered labor standards or, more specifically, the use of some predetermined motion time system, will enable engineers to provide the design team with an accurate labor-hour estimate. This information is vital in determining the labor cost of the future product or service. By using realistic values for the labor cost, the design team will be able to decide on the viability of the product or service in its current form. In situations where the project is not viable, the design team will be able to either refine its solution or stop the project well before the allocation of production resources.

Engineered labor standards greatly enhance the success rate of companies involved in a bidding process. By having an accurate picture of the labor cost associated with a project, a company will generate more realistic proposals. The prosperity of a company is at stake with every bidding process. The result of overestimating a project's labor costs usually results in a failure to secure the contract and ultimately in lost profits. On the other hand, the impact of underestimating a project's labor costs is often even more devastating because the company commences to produce units at a loss. This situation will be even more dramatic in the case of high-volume or long-term contracts.

With regard to pricing, the engineers must account for the relative importance of the labor component compared to the total cost of a product or service. It is important to pay more attention to products or services that require specialized labor. Whatever our belief in the importance of the labor content, it is prudent to clearly identify its contribution toward the total cost of the product. This will always enable the marketing team to devise an effective pricing strategy for products and services. It only makes sense to develop the engineered labor standards at the start of every new project to get maximum returns from the engineering investment.

Serving as Inputs to Production Systems

The advances in information technology have given companies new opportunities to improve their operations. The increasing power and decreasing costs of today's computer systems have led industries to become more and more dependent on information technology. The implementation of these systems has proven to be either a great asset to a company or its worst nightmare. Many of the failures had very little to do with the actual systems, but were mainly related to poor setups due to unreliable inputs. Work measurement is the only dependable source of information when dealing with data about time.

The manufacturing sector is focusing on reducing its operating costs by streamlining its planning process and reducing its inventory levels. As a result, many companies are implementing manufacturing resource planning (MRP II) systems and the just-in-time (JIT) manufacturing philosophy. Through better timing, these companies will achieve significant savings. The availability of accurate time measurements is critical to the success of these types of systems. When a company decides to implement a JIT strategy based on bad time estimates, it opens itself to disastrous consequences (out-of-stock situations, wasted labor hours, missed delivery promises, unbalanced work within a cell, etc.). This ultimately leads clients to lose confidence in the company. The use of work measurement techniques to build the operation times needed as inputs to these systems will greatly improve the company's effectiveness in building realistic plans.

The same thought process is observed in the warehousing and distribution operations. Through different supply chain initiatives, companies have made great strides in streamlining their distribution processes. Today most warehouses rely on sophisticated computerized systems called *warehouse management systems* (WMS) to improve overall efficiency and reduce cost per shipped case. These systems control inventory levels, manage work assignments, schedule operations, dispatch workers and material-handling equipment, manage labor hours, and so forth. The more these systems rely on time-based information to accomplish their scheduling and optimizing functions, the better they perform. The impressive size of many warehouses also causes direct problems on the labor management side. In recent years, warehouse operators have recognized the need for better and more efficient labor management tools. Software manufacturers have responded by providing labor control functionality to their core WMS products. The level of complexity of these labor control modules varies greatly; some offer simple labor reporting while others use sophisticated real-time labor standards calculations. Many of these systems generate a time goal for every work assignment. It is easy to understand that the time goal will be only as realistic as the time used in the calculation. Engineered labor standards greatly enhance the ability of these systems to produce accurate goal times. It is important to point out that most companies use this labor control functionality to issue disciplinary measures. In a unionized environment, the use of engineered labor standards becomes mandatory to give the system credibility.

In implementing and using these sophisticated systems, it is crucial to recognize that a complex system is not a substitute for accurate and timely information.

Serving as Inputs to Various Industrial Engineering Functions and Tools

How crucial are engineered labor standards to an industrial engineer? The best answer to this question lies at the beginning of an industrial engineer's apprenticeship period. If we analyze the assignments and exams given to an industrial engineering student during his schooling, we find that many questions make reference to a form of time value; whether it be a production time, a setup time, a delivery delay, or any other time values, this input turns out to be crucial in resolving the given question. For most students the source of this time value is irrelevant with as far as actually solving the problem. The time value is simply a piece of the puzzle to be assembled. As they make the transition from school to the real world, it dawns on most newly graduated engineers that this critical piece of information that was part of the question is now missing. Some initially try to use time estimates and quickly learn the importance of accurate and reliable time data. They inevitably have to turn to work measurement to build accurate time data.

The industrial engineer of the new millennium relies on computer software packages to solve common engineering problems to a far greater degree than did his or her predecessors. This approach is not a problem in itself, but it is rather some engineers' unwillingness to do the basic engineering work needed to obtain reliable inputs for these engineering packages that creates issues. Engineers must recognize the importance of providing inputs of the highest quality. They must also, by more traditional engineering means, be able to question the validity of the system's outputs. In the next pages, the important link that exists between common engineering functions and engineered labor standards will be carefully outlined.

Line Balancing. It is hard to understand how some companies believe they can balance their production lines without engineered labor standards. The following answer is often given: "We do not need to use standards to balance the line; the workers simply have to follow the speed of the line!" Some people seem to forget why we strive to balance production lines. The overall idea is to balance the workload of the workstations around the line and to adjust the speed of the line to achieve the desired throughput.

There are tremendous costs associated with an unbalanced production line. Without engineered labor standards it is extremely difficult to distinguish between what appears to be a balanced line and a truly balanced line. Workers may adapt a slower pace or use less productive methods to make it seem as though their cycle time is fully occupied. Since most people are not trained to accurately judge the quality of the work methods or to apply leveling to the observed operation, it is unlikely that any balancing problems will be discovered.

The benefits of using engineered labor standards in this case are twofold: the work methods will be enhanced, and total idle time will be minimized. Only by conducting a well-designed work measurement study will we obtain the finite elemental data needed to properly reorganize the line and thus achieve true line balancing. It is important to stress that the use of inaccurate values for one workstation impacts potentially the productivity of every other worker on the line. The potential for disaster is tremendous, as many workers will be unable to work at 100 percent efficiency. The untapped savings can rapidly reach hundreds of thousands of dollars in direct wages. Another direct result of a poorly balanced line is underutilization of the facility and the equipment, which further adds to the saving opportunities.

Simulation. The usefulness of simulation software packages has drastically improved in the last decade; not only are these packages more affordable, but they have also become user-friendly. Whereas these packages used to be limited to large companies or universities, this evolution has made them highly valuable tools for today's industrial applications. The extent to which this tool will be useful is directly proportional to the quality of the inputs supplied to the simulation model. The risks associated with using substandard data are enormous; not only are the immediate results of the model compromised, but the simulation process itself might be jeopardized.

The design of many simulation models requires the input of process times, response times, travel times, and other time data. The use of actual engineered times instead of fictitious time distribution will strengthen the results giving the simulation process the credibility it needs to be largely accepted as a valuable tool.

Engineered labor standards should be available where an existing process is being modeled. If the model simulates a theoretical process, the engineers can always resort to predetermined motion time systems to generate reliable times. There is no question that using engineered labor standards instead of time estimates will lengthen the overall time required for the simulation project, but it will greatly improve the quality of the results. The power of simulation lies in its ability to model reality and should therefore always rely on the best data source available.

Facilities Layout. Facilities layout has always been an important function of industrial engineers. One important criteria that the engineer always considers when working on designing a new layout is the capacity of the current and envisioned processes and operations. Unfortunately, it is very common to see the design team rely on crude estimates to assess the capabilities of workers, equipment, and processes. Here again, using engineered labor standards will improve the layout process by supplying accurate figures.

There are many consequences of using estimates instead of engineered labor standards. Frequently, the capacities used underestimate the actual output of the design. This will increase the cost of the layout alternatives, which may force the company to cancel the project. If the project does go ahead, a more affordable yet suboptimal solution may be chosen because of certain budgetary constraints. The new layout will most likely incur unnecessary capital expenditures that result from the initial estimates.

The reason that is often given for not using engineered labor standards as part of the information phase of the layout process is that work measurement represents an unjustifiable expense at such an early stage. This grossly undervalues the role that Engineered Labor Standards can play in evaluating the capability of the manufacturing and material-handling process. There are no valid arguments for not using work measurement at this stage of the layout design process. The costs of work measurement usually pale in comparison to the total cost of a layout. Furthermore, the engineered labor standards calculated for the purpose of analyzing the different layout options will quickly become production standards as soon as the chosen solution gets implemented.

Process Improvement. One of the most durable buzzwords to come out of the 1990s is *continuous process improvement* (CPI). There exist so many similarities between continuous process improvement and methods engineering that we can consider the terms interchangeable. These similarities mean that the symbiotic relationship between methods engineering and work measurement previously outlined holds true for continuous process improvement as well. The role of industrial engineering and engineered labor standards in the successful implementation of continuous process improvement initiatives becomes crucial. The only way to obtain the maximum from any continuous process improvement strategy is to rely on accurate measurement techniques that will quantify the exact impact of the initiative. In the absence of any scientific measurement, these projects simply become a forum in which participants voice extremely biased positions and solutions to what they perceive as problems. Under such conditions the outcome is unreliable and often leads to the implementation of solutions that have no real payback. In the case of continuous process improvement, the value of work measurement lies in its ability to accurately quantify the potential of current processes and foreseen alternatives.

Product Design. The presence of an industrial engineer will greatly enhance any design team by providing important knowledge on materials, processes, and people. By using work study skills, he or she will be able to help design a product that is feasible not only from the manufacturing side, but also from the financial side. Engineered labor standards provide the design team with accurate information regarding manufacturing times, which results in reliable cost estimates. No product should be designed without first answering an extremely critical question: Can this product be realistically priced and still generate acceptable profits? Clearly, answering this question at the earliest possible stage will give the design team the opportunity to adjust its design at the least costly step in the process. Should the product not turn out to be viable, the development may be aborted before any major manufacturing costs (equipment, tooling, layout changes, etc.) have been incurred. In the end, the company will avoid the worst-case scenario, which is to launch a product that will lose money throughout its entire life cycle.

An added benefit to developing the engineered labor standards at such an early stage is to provide manufacturing with production times as soon as the product hits the manufacturing lines. This will greatly accelerate the ramp-up phase of the production cycle and will also facilitate the actual engineered labor standard implementation, since it is always easier to have standards in place as a new task is introduced. This procedure tends to minimize employees' negative reactions to the introduction of labor standards.

JUSTIFICATION

An engineered labor standards project is to be looked upon as any other investment. The engineers should apply engineering economic analysis to calculate the return on investment (ROI), payback period, and any other financial indicators. The object of this section is to identify the key elements that the engineer should take into account when financially justifying the work measurement project. For a detailed explanation on the actual financial calculations, the reader should refer to Chap. 3.1 in this handbook.

Before starting any financial analysis, the overall impact of engineered labor standards on the company's performance needs to be thoroughly understood. This is best accomplished by answering two fundamental questions before going forward with the work measurement project. First of all, is it possible to efficiently manage without using engineered labor standards? Second, what is the cost of not using engineered labor standards?

The traditional way of justifying the implementation of engineered labor standards is to simply look at the direct labor cost savings. This myopic evaluation of the savings is attributable to the tremendous impact that work measurement has on these costs. In order to fully appreciate the extent of the savings associated with engineered labor standards, it is important to consider the impact of the standards on the overall profitability of the company. In justifying a work measurement project, the engineer should carefully review every aspect discussed in this chapter and calculate the appropriate savings for each.

When all the savings are properly identified, it is very common to see payback periods of less than one year. These implementations start generating additional profits within the same year, which means that the engineered labor standards' implementation may be autofinanced by using a selective, phased-in approach.

Some key attributes or variables of the work process to be analyzed will influence the relative payback of one task versus another. By better understanding these factors, the engineer can more appropriately select and sequence the operations to be studied. By properly accounting for these factors, it will be possible to prioritize the engineered labor standards' implementation in such a way as to extract the maximum from a phased-in approach. This will give a company maximum returns and enable it to maximize its labor standard coverage with minimal negative budgetary fluctuations. The following factors deserve additional attention.

1. *Number of employees.* The number of employees affected by the scope of the engineered labor standards will play a major impact on the potential absolute savings. The cost of defining engineered labor standards for one specific function often decreases when dealing with a large group of employees performing the same task. The associated savings will increase considerably as they impact more worker-hours. The following scenario clearly illustrates the impact of number of employees on the total savings. As a result of implementing engineered labor standards each employee produces an additional 25 percent of work. This means that the current conditions will require only 80 percent of the original staffing. An initial staff of 5 would yield a net saving of 1 employee, whereas an initial staff of 50 employees could be reduced by 10. Clearly, then, targeting tasks that employ a larger number of employees will result in higher savings.

2. *Hourly labor costs.* The implementation of engineered labor standards will reduce the number of worker-hours required to accomplish a given task. The generated savings result from the number of worker-hours saved and the labor rates. It is clear that the higher the wages, the more significant the financial savings. Some precautions must be taken when assessing the hourly labor costs. The hourly cost must be based on the *burdened rates,* which include both the paid hourly rate and the fringe benefits. Fringe benefits typically add anywhere from 20 to 50 percent to the hourly rate. Care must also be taken to use the hourly rate and fringe level of *only those employees* who will be affected by the standards. Is the standard to affect only part-time workers with lower wages and reduced benefits, or will it touch full-time workers with higher earnings and full benefits? Is the standard to impact only those at the bottom end of the full-time pay structure, or will it cross over different pay bands? Will there be a reduction in overtime hours at premium pay? A careful assessment of the workforce being impacted by the engineered labor standards will generate a much more accurate calculation of the savings.

3. *Complexity of the work measurement process.* The effort, and thus the cost, of setting up engineered labor standards will vary from task to task. The complexity of the work measurement process is linked to both the nature of the operation to be studied and to the work conditions and atmosphere that prevail. Some key factors to consider are the complexity of the task's work elements, the level of repetitiveness within the cycle, and the overall industrial relations climate. We must be particularly cautious in appraising industrial relations factors, since they tend to fluctuate over short time periods. What seemed like a very straightforward work measurement project might become an arduous implementation during a period of labor unrest.

4. *Complexity of the labor reporting.* Labor reporting is the front end of engineered labor standards; it provides feedback to both management and employees concerning the actual performance versus the standards. The complexity of this feedback mechanism varies greatly. In some instances the labor reporting costs are negligible, while at the other end of the spectrum they can be very high and involve hiring additional personnel, computer systems, data-capture equipment, and so on.

CONCLUSION

The outcomes of a carefully planned and implemented work measurement program are of critical importance to the survival of a company. Work measurement is the only available option that enables companies to set fair and realistic labor expectations. The credibility gained by engineered labor standards through the years ensures that in the event of an arbitration, the company will be able to successfully defend its labor expectations. The use of engineered labor standards will guarantee full utilization of a company's workforce and will also provide the company with a significant indicator of the abilities of its supervisors to maintain a proper work environment. This will allow companies to maximize resource utilization and strive toward an optimization of processes.

Engineered labor standards improve the ability of managers to make better decisions by providing them with a reliable and accurate source of information. This improved capability to plan and control will substantially improve the financial performance of any company.

The costs and risks of operating a business without engineered labor standards versus the cost of implementing and maintaining the standards is the only valid question. The tremendous savings and short payback periods associated with engineered labor standards usually put this issue to rest. Through a carefully planned implementation, the company should be able to generate substantial savings without negatively impacting its current budget.

Work measurement is part of the fundamental knowledge of industrial engineering. The crucial information it provides is critical to resolve many industrial engineering problems. Understanding the fundamentals of engineered labor standards is critical to the success of the industrial engineering profession.

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BIOGRAPHY

Georges Bishop holds a Bachelor of Engineering from l'École Polytechnique de Montréal. He is a senior vice president and cofounder of LXLI International Ltd., a Toronto-based industrial engineering consulting company specializing in work measurement and methods engineering, with the main focus on standards implementation. Bishop's main responsibility centers around designing engineered labor standards solutions. He has worked with both management and unions in addressing work measurement and engineered labor standards issues and is a recognized expert witness in the field. His consulting experience extends over many industrial sectors, including extensive experience in manufacturing, transport, distribution, and retail operations. Bishop is a certified MOST® trainer who has taught work measurement and methods engineering at both l'École Polytechnique de Montréal and l'Université de Sherbrooke. He has published articles on work measurement and engineered labor standards and is regularly asked to speak at international conferences on these subjects.

Source: MAYNARD'S INDUSTRIAL ENGINEERING HANDBOOK

CHAPTER 5.3

STANDARD DATA CONCEPTS AND DEVELOPMENT

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Historically, many businesses have made substantial investments in the study of individual jobs for the purpose of establishing and maintaining engineered standards. In most cases, the need for these detailed studies can be significantly reduced with the use of appropriate *standard data.* In many work environments, common processes are used to accomplish a wide variety of work. For example, in many manufacturing settings, a large number of parts are routed through only a few common operations. These work settings, as well as many in the service industries, are particularly well suited to the use of standard data.

By definition, *standard data* is the organization of work measurement data into useful, well-defined building blocks. Properly developed and implemented, many benefits will result from the use of standard data. These benefits include reduced development time and cost, higher coverage level, easier standards maintenance, and increased consistency, accuracy, understanding, and acceptance. Having standard data also enables more accurate planning, costing, estimating, and the use of advanced data application technology.

This chapter will discuss the concepts, principles, and practices of data standard development. The benefits and limitations of standard data will also be discussed, with practical examples and advice on data development provided. Work measurement techniques, such as Maynard Operation Sequence Technique (MOST®), will be mentioned as the basis for standard data development. The reader who is not familiar with these and other work measurement techniques would benefit from reading Chap. 5.1.

STANDARD DATA—UNDERSTANDING THE CONCEPT

The goal of standard data is to provide a means to establish and maintain standards quickly and easily without unduly effecting the accuracy of the results. The concept of standard data is quite logical, and can be easily understood by studying the following definition from *Maynard Industrial Engineering Handbook,* 4th edition:

> Standard data is the organization of work elements into useful, well-defined building blocks. The size, content, and number of these building blocks depends upon the accuracy desired, nature of the work, and the flexibility required. The resulting data can be used as the basis for determining time standards on work that is similar to that from which the data were collected without making additional measurement studies.

In theory, this definition could apply to data at almost any level. For example, predetermined motion time systems (PMTSs) such as MOST and methods time measurement (MTM) are, by definition, standard data systems, since they provide standard time values for activities (MOST) and basic motions (MTM). However, our definition also describes how to determine the “size, content, and number of these building blocks.” To have useful standard data, this determination must be made relative to the application. Basic MTM motion data is not practical and useful as standard data in most operations, and it would be especially difficult to use in a heavy assembly or fabrication operation, for example. To be useful, the data must be built up to a higher level. Therefore, the practical definition of standard data that we will use is

> Standard data is work measurement data that is built up, using a work measurement technique, into useful, well-defined, and easily applied building blocks. These building blocks will be structured and defined to a level that is most suitable for the application.

The opposite of standard data is *direct measurement,* or the direct study of each operation for the purpose of setting a standard for that operation only. This approach has some benefits in certain situations. Direct measurement will be discussed later in this chapter.

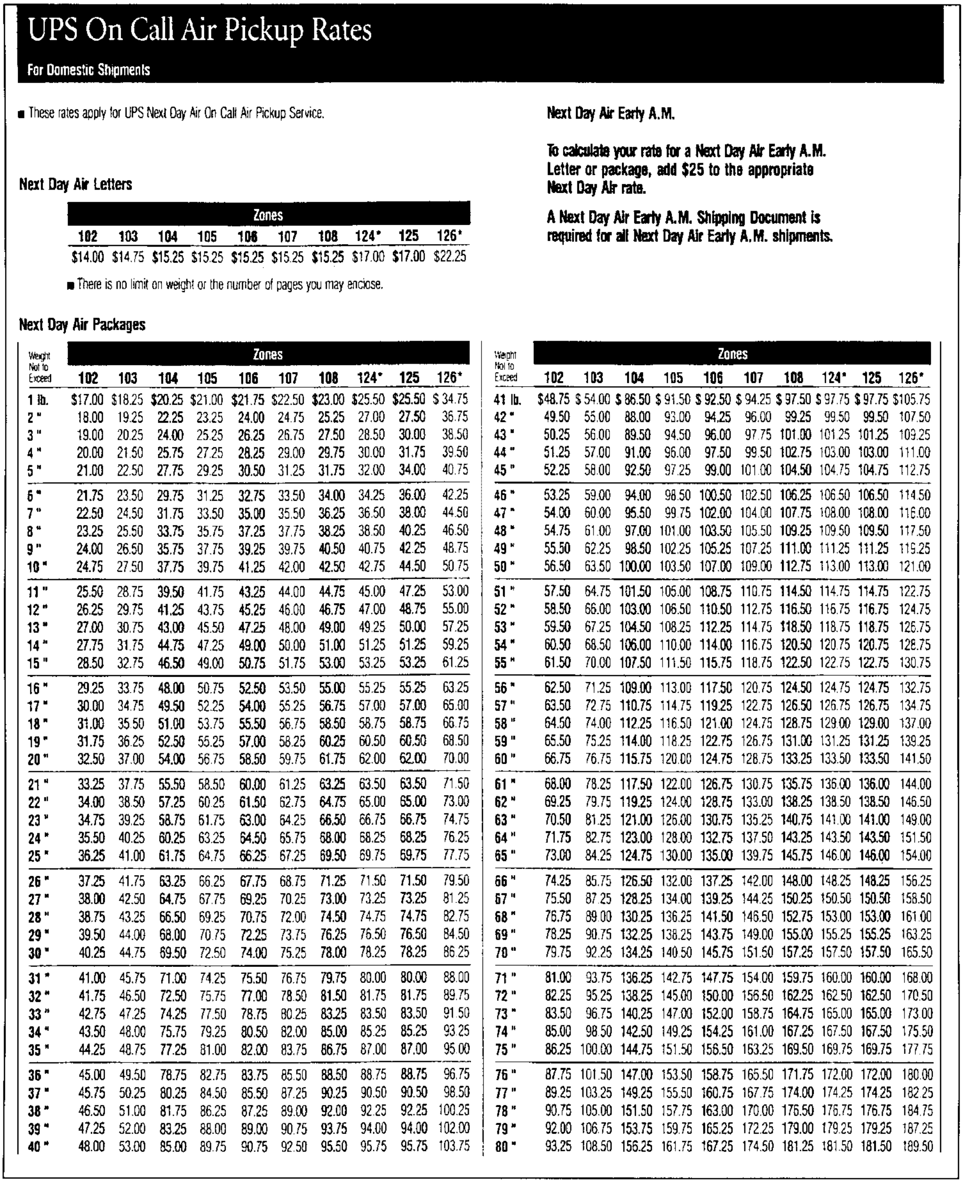
Engineered standards and standard data are often considered useful for establishing work standards for manufacturing (and sometimes service industry) operations. However, there are many examples of standard data, other than engineered work measurement, in use today. Some types of standard data are encountered during our everyday lives: examples are postage and shipping rate tables, insurance actuarial tables and formulas, automotive service rate schedules, National Automobile Dealers Association (NADA) used car value tables, and moving or freight company cost-estimating guidelines. In some industries, standard data has been commonly used for years. For example, the building trades industry uses standard data for job estimating and costing based primarily on building dimensions, materials required, and site conditions. An example of this type of data is shown in Fig. 5.3.1, which is a UPS air shipping rate table for the eastern United States. The charge for shipping a package from the eastern United States to any of the specified zones is not the same. Also, the *actual* cost of shipping various 10-lb packages could vary significantly. However, it would be prohibitively expensive to establish the true cost of shipping every package. If this data is carefully developed and correctly applied, it serves the purpose of ensuring a profitable operation without unnecessary cost. This same concept can be applied to the development of engineered standards.

BENEFITS AND LIMITATIONS OF STANDARD DATA

Benefits

Many benefits will result from the use of well-defined standard data. Where good standard data has been introduced, these benefits are readily recognized by industrial engineers and production management. Some of the more significant benefits are

- *Reduced development time and costs.* Although standard data development does require an up-front investment in design and structure definition, this investment pays off in many ways, including a reduction in the overall time to develop engineered standards. This is primarily because without standard data the measurement of many tasks would be repeated extensively.
- *Higher coverage level.* Since standard data reduces the development time, higher levels of coverage can be achieved with the same investment.
- *Easier maintenance.* Standard data provides a set of building blocks that will be used extensively throughout the operation. Maintenance of these basic building blocks will reduce or eliminate the need to maintain many individual standards.



UPS On Call Air Pickup Rates

For Domestic Shipments

- These rates apply for UPS Next Day Air On Call Air Pickup Service.

Next Day Air Early A.M.

To calculate your rate for a Next Day Air Early A.M. Letter or package, add $25 to the appropriate Next Day Air rate.

A Next Day Air Early A.M. Shipping Document is required for all Next Day Air Early A.M. shipments.

Next Day Air Letters

Zones 102	103	104	105	106	107	108	124*	125	126*
$14.00	$14.75	$15.25	$15.25	$15.25	$15.25	$15.25	$17.00	$17.00	$22.25

- There is no limit on weight or the number of pages you may enclose.

Next Day Air Packages

Weight Not to Exceed	Zones 102	103	104	105	106	107	108	124*	125	126*
1 lb.	$17.00	$18.25	$20.25	$21.00	$21.75	$22.50	$23.00	$25.50	$25.50	$ 34.75
2 "	18.00	19.25	22.25	23.25	24.00	24.75	25.25	27.00	27.50	36.75
3 "	19.00	20.25	24.00	25.25	26.25	26.75	27.50	28.50	30.00	38.50
4 "	20.00	21.50	25.75	27.25	28.25	29.00	29.75	30.00	31.75	39.50
5 "	21.00	22.50	27.75	29.25	30.50	31.25	31.75	32.00	34.00	40.75
6 "	21.75	23.50	29.75	31.25	32.75	33.50	34.00	34.25	36.00	42.25
7 "	22.50	24.50	31.75	33.50	35.00	35.50	36.25	36.50	38.00	44.50
8 "	23.25	25.50	33.75	35.75	37.25	37.75	38.25	38.50	40.25	46.50
9 "	24.00	26.50	35.75	37.75	39.25	39.75	40.50	40.75	42.25	48.75
10 "	24.75	27.50	37.75	39.75	41.25	42.00	42.50	42.75	44.50	50.75
11 "	25.50	28.75	39.50	41.75	43.25	44.00	44.75	45.00	47.25	53.00
12 "	26.25	29.75	41.25	43.75	45.25	46.00	46.75	47.00	48.75	55.00
13 "	27.00	30.75	43.00	45.50	47.25	48.00	49.00	49.25	50.00	57.25
14 "	27.75	31.75	44.75	47.25	49.00	50.00	51.00	51.25	51.25	59.25
15 "	28.50	32.75	46.50	49.00	50.75	51.75	53.00	53.25	53.25	61.25
16 "	29.25	33.75	48.00	50.75	52.50	53.50	55.00	55.25	55.25	63.25
17 "	30.00	34.75	49.50	52.25	54.00	55.25	56.75	57.00	57.00	65.00
18 "	31.00	35.50	51.00	53.75	55.50	56.75	58.50	58.75	58.75	66.75
19 "	31.75	36.25	52.50	55.25	57.00	58.25	60.25	60.50	60.50	68.50
20 "	32.50	37.00	54.00	56.75	58.50	59.75	61.75	62.00	62.00	70.00
21 "	33.25	37.75	55.50	58.50	60.00	61.25	63.25	63.50	63.50	71.50
22 "	34.00	38.50	57.25	60.25	61.50	62.75	64.75	65.00	65.00	73.00
23 "	34.75	39.25	58.75	61.75	63.00	64.25	66.50	66.75	66.75	74.75
24 "	35.50	40.25	60.25	63.25	64.50	65.75	68.00	68.25	68.25	76.25
25 "	36.25	41.00	61.75	64.75	66.25	67.25	69.50	69.75	69.75	77.75
26 "	37.25	41.75	63.25	66.25	67.75	68.75	71.25	71.50	71.50	79.50
27 "	38.00	42.50	64.75	67.75	69.25	70.25	73.00	73.25	73.25	81.25
28 "	38.75	43.25	66.50	69.25	70.75	72.00	74.50	74.75	74.75	82.75
29 "	39.50	44.00	68.00	70.75	72.25	73.75	76.25	76.50	76.50	84.50
30 "	40.25	44.75	69.50	72.50	74.00	75.25	78.00	78.25	78.25	86.25
31 "	41.00	45.75	71.00	74.25	75.50	76.75	79.75	80.00	80.00	88.00
32 "	41.75	46.50	72.50	75.75	77.00	78.50	81.50	81.75	81.75	89.75
33 "	42.75	47.25	74.25	77.50	78.75	80.25	83.25	83.50	83.50	91.50
34 "	43.50	48.00	75.75	79.25	80.50	82.00	85.00	85.25	85.25	93.25
35 "	44.25	48.75	77.25	81.00	82.00	83.75	86.75	87.00	87.00	95.00
36 "	45.00	49.50	78.75	82.75	83.75	85.50	88.50	88.75	88.75	96.75
37 "	45.75	50.25	80.25	84.50	85.50	87.25	90.25	90.50	90.50	98.50
38 "	46.50	51.00	81.75	86.25	87.25	89.00	92.00	92.25	92.25	100.25
39 "	47.25	52.00	83.25	88.00	89.00	90.75	93.75	94.00	94.00	102.00
40 "	48.00	53.00	85.00	89.75	90.75	92.50	95.50	95.75	95.75	103.75
41 lb.	$48.75	$ 54.00	$ 86.50	$ 91.50	$ 92.50	$ 94.25	$ 97.50	$ 97.75	$ 97.75	$105.75
42 "	49.50	55.00	88.00	93.00	94.25	96.00	99.25	99.50	99.50	107.50
43 "	50.25	56.00	89.50	94.50	96.00	97.75	101.00	101.25	101.25	109.25
44 "	51.25	57.00	91.00	96.00	97.50	99.50	102.75	103.00	103.00	111.00
45 "	52.25	58.00	92.50	97.25	99.00	101.00	104.50	104.75	104.75	112.75
46 "	53.25	59.00	94.00	98.50	100.50	102.50	106.25	106.50	106.50	114.50
47 "	54.00	60.00	95.50	99.75	102.00	104.00	107.75	108.00	108.00	116.00
48 "	54.75	61.00	97.00	101.00	103.50	105.50	109.25	109.50	109.50	117.50
49 "	55.50	62.25	98.50	102.25	105.25	107.25	111.00	111.25	111.25	119.25
50 "	56.50	63.50	100.00	103.50	107.00	109.00	112.75	113.00	113.00	121.00
51 "	57.50	64.75	101.50	105.00	108.75	110.75	114.50	114.75	114.75	122.75
52 "	58.50	66.00	103.00	106.50	110.50	112.75	116.50	116.75	116.75	124.75
53 "	59.50	67.25	104.50	108.25	112.25	114.75	118.50	118.75	118.75	126.75
54 "	60.50	68.50	106.00	110.00	114.00	116.75	120.50	120.75	120.75	128.75
55 "	61.50	70.00	107.50	111.50	115.75	118.75	122.50	122.75	122.75	130.75
56 "	62.50	71.25	109.00	113.00	117.50	120.75	124.50	124.75	124.75	132.75
57 "	63.50	72.75	110.75	114.75	119.25	122.75	126.50	126.75	126.75	134.75
58 "	64.50	74.00	112.25	116.50	121.00	124.75	128.75	129.00	129.00	137.00
59 "	65.50	75.25	114.00	118.25	122.75	126.75	131.00	131.25	131.25	139.25
60 "	66.75	76.75	115.75	120.00	124.75	128.75	133.25	133.50	133.50	141.50
61 "	68.00	78.25	117.50	122.00	126.75	130.75	135.75	136.00	136.00	144.00
62 "	69.25	79.75	119.25	124.00	128.75	133.00	138.25	138.50	138.50	146.50
63 "	70.50	81.25	121.00	126.00	130.75	135.25	140.75	141.00	141.00	149.00
64 "	71.75	82.75	123.00	128.00	132.75	137.50	143.25	143.50	143.50	151.50
65 "	73.00	84.25	124.75	130.00	135.00	139.75	145.75	146.00	146.00	154.00
66 "	74.25	85.75	126.50	132.00	137.25	142.00	148.00	148.25	148.25	156.25
67 "	75.50	87.25	128.25	134.00	139.25	144.25	150.25	150.50	150.50	158.50
68 "	76.75	89.00	130.25	136.25	141.50	146.50	152.75	153.00	153.00	161.00
69 "	78.25	90.75	132.25	138.25	143.75	149.00	155.00	155.25	155.25	163.25
70 "	79.75	92.25	134.25	140.50	145.75	151.50	157.25	157.50	157.50	165.50
71 "	81.00	93.75	136.25	142.75	147.75	154.00	159.75	160.00	160.00	168.00
72 "	82.25	95.25	138.25	145.00	150.00	156.50	162.25	162.50	162.50	170.50
73 "	83.50	96.75	140.25	147.00	152.00	158.75	164.75	165.00	165.00	173.00
74 "	85.00	98.50	142.50	149.25	154.25	161.00	167.25	167.50	167.50	175.50
75 "	86.25	100.00	144.75	151.50	156.50	163.25	169.50	169.75	169.75	177.75
76 "	87.75	101.50	147.00	153.50	158.75	165.50	171.75	172.00	172.00	180.00
77 "	89.25	103.25	149.25	155.50	160.75	167.75	174.00	174.25	174.25	182.25
78 "	90.75	105.00	151.50	157.75	163.00	170.00	176.50	176.75	176.75	184.75
79 "	92.00	106.75	153.75	159.75	165.25	172.25	179.00	179.25	179.25	187.25
80 "	93.25	108.50	156.25	161.75	167.25	174.50	181.25	181.50	181.50	189.50

FIGURE 5.3.1 UPS next day air shipping rate table—eastern United States.

- *Increased consistency.* Since the standards will be based on a set of common building blocks, which will be applied to many different operations, consistency of measured methods and times is improved.
- *Increased accuracy.* Standard data, when properly designed, will provide a certain level of accuracy by design. It may be more accurate than direct measurement techniques, since the actual measurement work is typically completed one time in a very controlled environment; the resulting data is then applied widely, according to specific application rules.

- *Better understanding and acceptance.* Because a common set of data is being used, understanding and acceptance can be improved. All that needs to be understood and accepted is the basic set of data. Once this is achieved, acceptance of the data as it is applied will typically be improved. The need to prove the validity of each individual standard should be reduced. Understanding will also increase since the basic data will always be familiar.
- *Better use of advanced application technology.* The term *application technology* suggests that the standard data will be used, or applied, to set standards. This process can be greatly simplified by the use of expert systems technology, with standards produced electronically. In some cases, the need for human intervention can be completely eliminated.
- *Easier transportability and benchmarking.* If common processes in multiple facilities and locations are used, standard data can be easily transported and quickly applied. This allows for easy benchmarking and comparison of operations. If your operation involves common processes, you might also find that standard data already exists and can be easily obtained and validated.

Limitations

Generally speaking, standard data can greatly simplify the task of developing and maintaining engineered standards. However, there are limitations to the usefulness of this approach, as well as situations where the approach is simply not valid:

Very short cycle, highly repetitive operations. Highly repetitive operations normally involve a very short cycle. These operations do not lend themselves well to a standard data approach, mainly due to the requirements for accuracy and detail.

Few standards needed. If only a few standards are to be set, standard data development will not be cost-effective. Direct measurement should be used.

Need for detailed method descriptions. Since standard data is developed to cover a wide variety of situations, detailed descriptions for each possible application will not exist. If standards will be used to provide detailed-level method descriptions, standard data may not be appropriate. These descriptions must be added at each point of application where required. Often systems other than the standards system can be used to supply these operator instructions.

Acceptance. We discussed acceptance earlier in relation to how it can improve through the use of standard data. However, this is not always the case. In some cases, especially where people have come to expect the use of a very detailed direct measurement approach, acceptance of standard data can be a problem. This is normally overcome through education and communication efforts.

Design for assembly (DfA). DfA normally involves a very detailed measurement process to arrive at the simplest or most cost-effective assembly process steps. Since standard data will typically rely on averages and methods representative of a wide variety of similar work, the level of detail required for DfA may not be satisfied with standard data.

Improper use. Standard data offers many advantages. However, if adequate application instructions are not written and closely followed, the data may be improperly applied. One of the most common forms of misapplication is "stretching" the data to cover application for which it was not intended. Improper application may be more common with standard data than with direct measurement, since detailed study is not required with standard data use.

In summary, standard data is useful in most cases. Even in the few situations where limitations are encountered, there normally is still some use for standard data or some means of overcoming the limitation. The reader will better understand these means after reading the section, Standard Data Development Guidelines.

PRINCIPLES OF STANDARD DATA

Standard data can be applied to simplifying the task of developing engineered labor standards in almost any business or industry. The most important ingredient for success is the understanding of four essentials for successful development and application:

1. *Top-down approach* to development
2. An understanding of the *building blocks concept* of standard data development
3. *Comprehensive training and involvement,* and support during the development and implementation phases.
4. Proper *documentation of the data* during the development and application steps

Top-down Approach

The most important principle in standard data development is that the approach is critical to the results. Useful, accurate standard data will result only from taking the right development approach. Development must follow a closely controlled process, with a significant amount of the effort devoted to up-front design and testing. This highly structured approach is known as the *top-down approach.* This approach will be described at length in subsequent sections.

Building Blocks Concept

It is important to understand the building blocks concept of standard data development. This concept is fundamental to the understanding and development of useful standard data. In a well-conceived standard data structure, useful building blocks typically exist at several levels, as illustrated in Fig. 5.3.2.

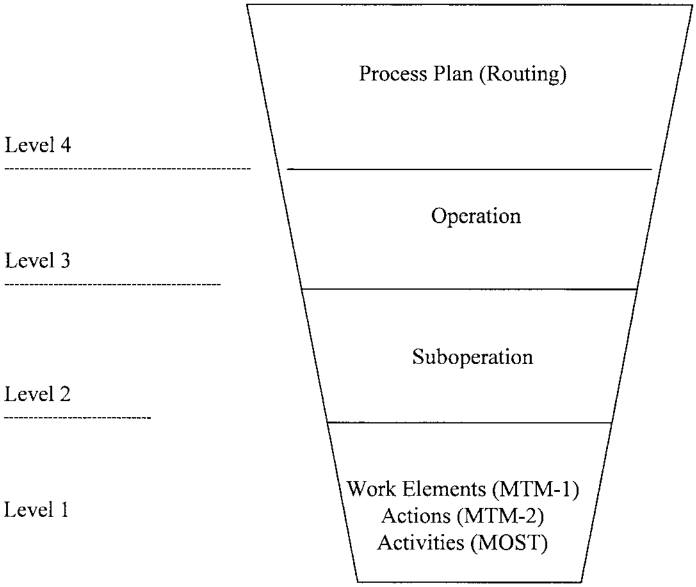
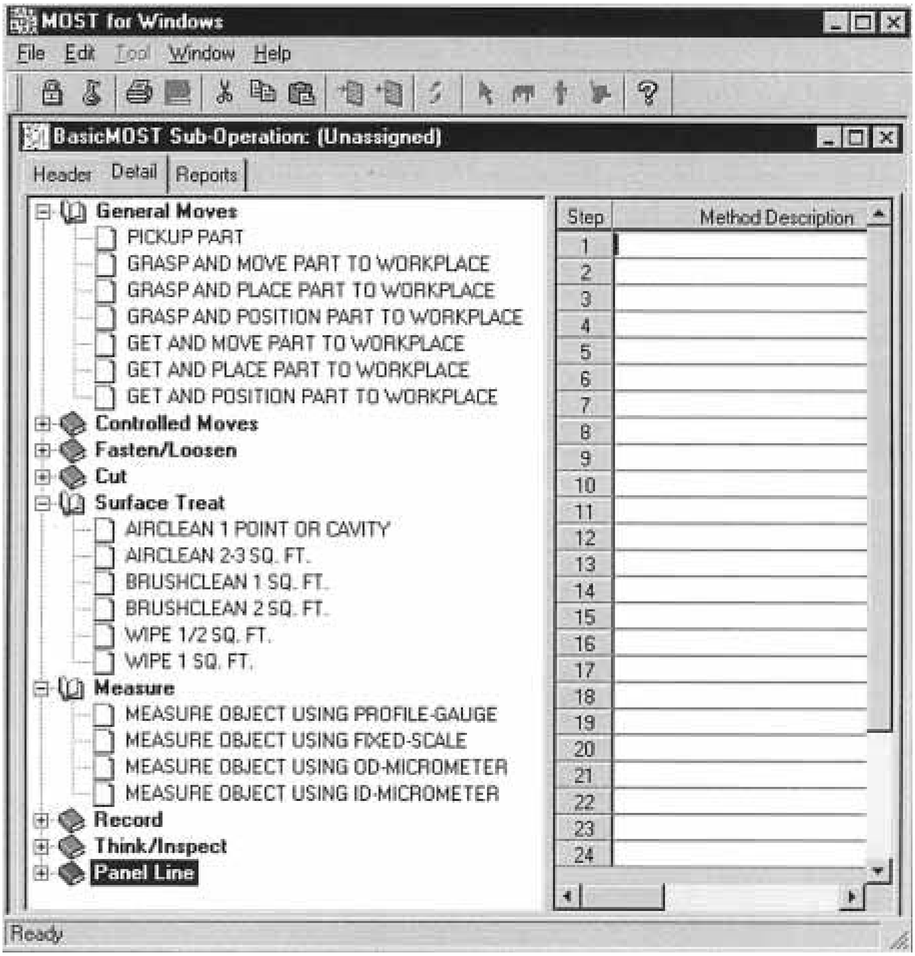


FIGURE 5.3.2 Building block concept.

The lowest level of data are basic work elements. Data at this level typically consists of common motion patterns that are very general in nature. This basic data can be used in most any work environment and can be developed with any valid work measurement technique. Fig. 5.3.3 depicts basic work element data from the MOST® for Windows software program. As you progress up the levels, the data becomes more and more specific to the application. The data in the following illustrations is an example from a machining application. Note the use of data elements from the lower levels at each subsequent higher level.



- **General Moves**
  - PICKUP PART
  - GRASP AND MOVE PART TO WORKPLACE
  - GRASP AND PLACE PART TO WORKPLACE
  - GRASP AND POSITION PART TO WORKPLACE
  - GET AND MOVE PART TO WORKPLACE
  - GET AND PLACE PART TO WORKPLACE
  - GET AND POSITION PART TO WORKPLACE
- **Controlled Moves**
- **Fasten/Loosen**
- **Cut**
- **Surface Treat**
  - AIRCLEAN 1 POINT OR CAVITY
  - AIRCLEAN 2-3 SQ. FT.
  - BRUSHCLEAN 1 SQ. FT.
  - BRUSHCLEAN 2 SQ. FT.
  - WIPE 1/2 SQ. FT.
  - WIPE 1 SQ. FT.
- **Measure**
  - MEASURE OBJECT USING PROFILE-GAUGE
  - MEASURE OBJECT USING FIXED-SCALE
  - MEASURE OBJECT USING OD-MICROMETER
  - MEASURE OBJECT USING ID-MICROMETER
- **Record**
- **Think/Inspect**
- **Panel Line**

FIGURE 5.3.3 Basic work element data—MOST® for Windows.

Level 2 data is often referred to as suboperation data. Data at this level is typically composed of a sequence of one or several fundamental motions and machine/process activities. An example of data at this level is shown in Fig. 5.3.4. This data was built up from basic work elements. The data at this level is more specific, but is useful on a variety of different machining operations.

Sub-Operation Report—Method / TMU
H. B. Maynard and Co.

Sub-Op ID:	1576	Status:	Public
Description:	UNLOAD FINISHED PART FROM PNEUMATIC CHUCK, RELOAD STOCK		
Activity:	MOVE	Object:	PART
Prod/Equip:		Tool:	HAND
Size/Capacity:		WA Origin:	MACHINE
WA Number:		Other:	
Unit of Measure:	PART	OFG:	2
WorkArea ID:		Starting Oper:	
Starting Location:		Total Time:	280
Operator Instr:			
Applicator Instr:	Includes removing part, cleaning chuck with air hose, and placing a pieceof stock in chuck.		
Safety Instr:			
IE:	MCS	Issue:	1
Create Data:	2/10/00	Effect Date:	2/10/00

Method Steps

Step	Method Description	Freq	Simo	TMU	Total
1	GRASP AND MOVE PART TO WORKPLACE	1.000	N	40	40
	A1 B0 G1 A1 B0 P1 A0				
2	PUSH/PULL/ROTATE BUTTONS/SWITCH/KNOB	1.000	N	30	30
	A1 B0 G1 M1 X0 I0 A0	1.000	N	120	120
3	AIRCLEAN 1 POINT OR CAVITY				
	A1 B0 G1 A1 B0 P1 S6 A1 B0 P1 A0				
4	GRASP AND MOVE PART TO WORKPLACE	1.000	N	40	40
	A1 B0 G1 A1 B0 P1 A0				
5	SLIDE OBJECT	1.000	N	50	50
	A1 B0 G1 M3 X0 I0 A0				

FIGURE 5.3.4 Example of suboperation data (level 2).

Level 3 is known as the operation level. As before, data at this level is built up from lower-level data. This data is very specific to machining operations, and is probably very specific to a particular company and facility. However, since the same (or very similar) operations may be performed on multiple parts, this level can also be used as standard data. Typically, group technology is used at this level to group parts into common "families," thereby reducing the number of required standard data items (operations) required at this level (see Fig. 5.3.5).

Level 4 is the highest level of data in this example. Data at this level is very specific and unique. This level is known as the process plan. In traditional manufacturing terms, this level of data is the part routing. It is also possible to utilize group technology at this level. Figure 5.3.6 is an example of data at this level.

As shown in the preceding examples, building blocks of data can exist at different levels. Figure 5.3.2 shows four levels of data. It is typical for manufacturing organizations to use three or four levels. At the lowest level, this data can be backed up with a PMTS, a time study, or estimates.

Operation Report—Combined
H. B. Maynard and Co.

Operation ID:	1	Status:	PUBLIC
Description:	TURN SHAFT ON CNC TURNING CENTER		
Part Num:	1234-****	Operator Number:	040
Part Name:	DRIVE SHAFT		
Total:	0.04813	Total/Piece:	0.04813
Department:	MCH	Work Center:	300
Worksheet ID:		Material:	1040
Run/Setup:	R	Pieces/Cycle:	1.000
Manual Allow:	15.000	Process Allow:	15.000
Operator Instr:			
Applicator Instr:	Includes all steps to turn a drive shaft complete. Applies to CNC turning for all 1234 series parts.		
Safety Instr:			
IE:	MCS	Issue:	3
Create Data:	5/9/00	Effect Date:	2/10/00

Step:	ID	Title	Freq.	Hours:	Internal To:	
1	1576	UNLOAD FINISHED PART FROM PNEUMATIC	1.000	0.00280	0	LEVEL 2 DATA
2	1577	START MACHINE PROCESS	1.000	0.00100	0	
3	1578	PROCESS TIME—TURN SHAFT	1.000	0.03662	0	
4	1577	STOP MACHINE PROCESS	1.000	0.00100	0	
5	1579	INSPECT TWO DIMENSION ON PART	1/10	0.00010	0	
6	1580	REMOVE CHIPS FROM TURNING CENTER BED	1/200	0.00033	0	

Type of Work	Elemental Time	Allowance Percent	Allowance Time	Standard Time
External Manual	0.04185	15.000	0.00628	0.04813
Assigned Internal	0.00000	15.000	0.00000	0.00000
Process Time	0.00000	15.000	0.00000	0.00000
Std (Hours/Cycle)	0.04185		0.00628	0.04813
	Pieces/Cycle:	1.000		
	Standard Hours/Piece:	0.048113		
	Pieces/Hours@100%:	20.78		

FIGURE 5.3.5 Example of operation data (level 3).

Training and Involvement

The development and use of standard data, like all major initiatives, requires wide organizational support. This support came come in a number of forms, but the following are critical:

- Participation in and support of training programs designed to provide all levels of management an understanding of standard data principles and the benefits.

Plan Report—Method
H. B. Maynard and Co.

Plan ID:	1	Status:	Public
Description:	MANUFACTURE DRIVE SHAFT—SMALL		
Part Number:	1234-5678	Drawing No.:	112AD
Part Name:	DRIVE SHAFT	Revision:	2
Product Code:	ADC	Router Type:	R
Model:	2		
Material:	1020	Unit:	PART
Run Time:	0.19545	Setup Time:	0.00000
Operator Instr:			
Applicator Instr:			
Safety Instr:			
Applicator:	MCS	Issue:	4
Create Data:	5/9/00	Effect Date:	2/10/00

Step	Oper ID	Description	Oper Number	Work Center	Dept	Run/ Setup	Freq.	Total Time	Time/Piece
1	2	SAW SHAFT STOCK—SMALL	010	100	MCH	R	1.000	0.04330	0.04330
2	1	TURN SHAFT ON CNC TURNING CENTER	040	300	MCH	R	1.000	0.02344	0.02344
3	3	FINISH TURN SHAFT	050	350	MCH	R	1.000	0.02344	0.02344
4	4	MILL SLOTS—SMALL SHAFT	060	400	MCH	R	1.000	0.05444	0.05444
5	5	HEAT TREAT—SMALL PART	070	500	MCH	R	1.000	0.00300	0.00300
6	6	FINISH GRAND FLATS—SMALL SHAFT	080	600	MCH	R	1.000	0.02314	0.02314
				Run Time (Hours):			0.19545		Level 3 Data
				Setup Time (Hours):				0.00000	

FIGURE 5.3.6 Example of process plan data (level 4).

- Involvement in standard operating practices committees that are established to identify and document the correct practices on which to base the standard data.
- Information meetings designed to review and verify facts developed by the industrial engineer relative to methods, workplace layouts, quality requirements, tooling and safety procedures. These meetings should be conducted for the review of existed and proposed methods.
- Review of documented materials related to the respective responsibilities of line management, staff groups, and associates or production workers to achieve the maximum results from the application of standard data.
- Participation in studies to validate the standard data against actual conditions (see top-down analysis).

The reader who is not familiar with the implementation of standards would benefit from reading Chap. 5.7.

Documentation

When developing and applying standard data, good documentation procedures are essential for several reasons. First, the scope of application of the data must be controlled. Data is developed with application rules, and these rules must be documented. Otherwise, the data application cannot be adequately controlled. Second, since conditions will constantly change, it is important to document the conditions in effect when the data was developed so that standards can be updated and maintained. In some cases, it is necessary to justify that changes should be made. In these cases, it is especially important to have good documentation. The documentation should include the following:

- The scope of application for the data. What can be covered, and what is not covered.
- Conditions in effect when the data was developed.
- Rules describing how to apply and maintain the data.
- Tools, such as worksheets, for use in applying the data.

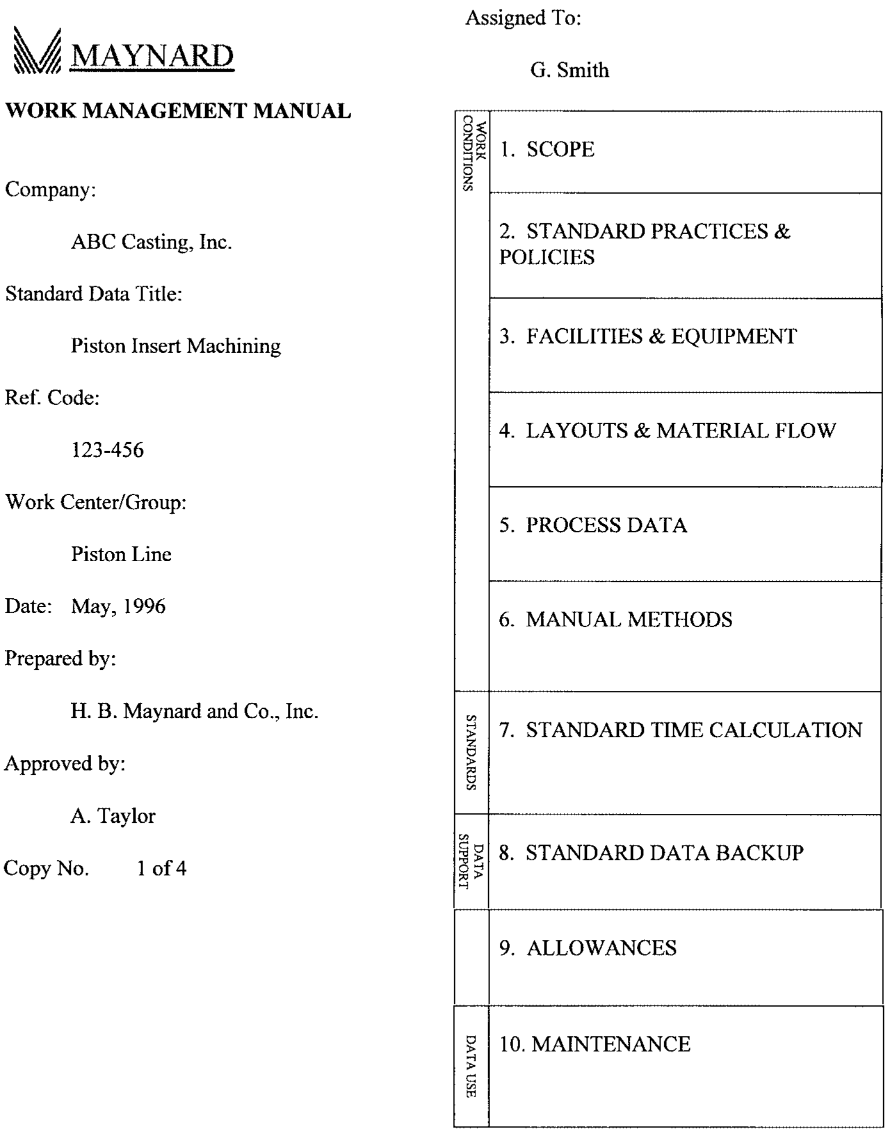
A common approach to documentation of standard data is the development of a work management manual (WMM). This approach is further defined in the next section, *Standard Data Development Guidelines.* A sample outline of a work management manual for a foundry operation is shown in Fig. 5.3.7.

The objectives for developing a WMM are

- Provide a means for documenting the conditions that existed at the time the standard data was developed. This is important for maintaining the data.
- Clearly identify the scope of application for the standard data.
- Document guidelines and tools for application of the data.
- Describe, for future reference, the process followed in development of the standard data.
- Provide the documentation necessary to allow the audit of any standard within the scope of the WMM.

The work management manual section included in this chapter is written as a content description guide to give the reader direction in how to properly document standard data. The guidelines are not intended to be all-inclusive. References to company procedure and policy manuals will reduce the need to include this documentation in the work management manual.

STANDARD DATA CONCEPTS AND DEVELOPMENT



MAYNARD

WORK MANAGEMENT MANUAL

Company:

ABC Casting, Inc.

Standard Data Title:

Piston Insert Machining

Ref. Code:

123-456

Work Center/Group:

Piston Line

Date: May, 1996

Prepared by:

H. B. Maynard and Co., Inc.

Approved by:

A. Taylor

Copy No. 1 of 4

Assigned To:

G. Smith

WORK CONDITIONS	1. SCOPE
	2. STANDARD PRACTICES & POLICIES
	3. FACILITIES & EQUIPMENT
	4. LAYOUTS & MATERIAL FLOW
	5. PROCESS DATA
	6. MANUAL METHODS
STANDARDS	7. STANDARD TIME CALCULATION
DATA SUPPORT	8. STANDARD DATA BACKUP
	9. ALLOWANCES
DATA USE	10. MAINTENANCE

FIGURE 5.3.7 Work management manual—table of contents.

STANDARD DATA DEVELOPMENT GUIDELINES

Successfully developing useful standard data, that is, moving from principle to practice, is a challenging task. Proper development is critical to having useful and accurate data. The initial task of design and data structure development is the most important step. Errors in structure or data design at this stage will reappear exponentially later in application of the data. It is quite easy to minimize the importance of this up-front investment. Successful development normally requires that an expert be involved to guide the development project. This section will provide general development guidelines.

In many cases, some standard data development will occur simply as a natural outgrowth of the (direct) measurement process. For example, an industrial engineer, charged with developing standards for a manufacturing assembly process, may start by measuring each assembly station. However, he or she will soon find that tasks are repeating from one assembly station to the next, and will then begin to structure elements of data to be reused at subsequent stations. The result is standard data, albeit poorly designed. At this point, many opportunities for simplification have been overlooked, or are an afterthought. The approach, even if unintentional, is known as *bottom-up standard data.*

The correct approach to standard data involves much up-front design work. This method is known as the *top-down approach* to standard data development. It begins with finding the answers to a number of design-related questions such as

Which operations are to be covered with standards?

For what purpose will the standards be used?

How accurate must the standards be?

Who will set the standards?

What information will be available when setting standards?

Is there an ongoing need to set standards, or can most of the standards be set up front?

Will the standards change often?

How much attention will be given to ongoing standards maintenance?

Good standard data development always starts with a top-down analysis and design stage. The top-down approach consists of seven steps, as shown in Fig. 5.3.8.

Organization of Work

A top-down analysis begins with determining the scope of the standards project. The first step is to determine the "top." This step is essentially a project-planning step. All areas to be covered by standards are identified. Similarities and differences between these areas are considered. Needs versus project budget may be a consideration, with the understanding that it may be more cost-effective in the long term to broaden the scope initially. For example, many areas within a manufacturing plant may have similar operations. In this case, it would be more logical to include these areas within the scope of a single development project. If your company has multiple facilities with similar operations, would it be feasible to develop companywide standard data?

Five questions to consider in determining the top are

1. What is the organizational structure of the facility? Are functional areas used, or is the plant set up in a cellular arrangement?
2. What is the variety of operations or products produced?
3. Are common operations used throughout?
4. Are major re-layouts, product changes, or equipment changes planned in any areas?
5. What resources are available to complete the development?

After answering these questions, you can identify a top for your development project. Section 1 of the work management manual can also be completed. The requirements for this section are further defined in Fig. 5.3.9. Now your scope will be well defined, and you are ready to move on to the activity analysis phase.

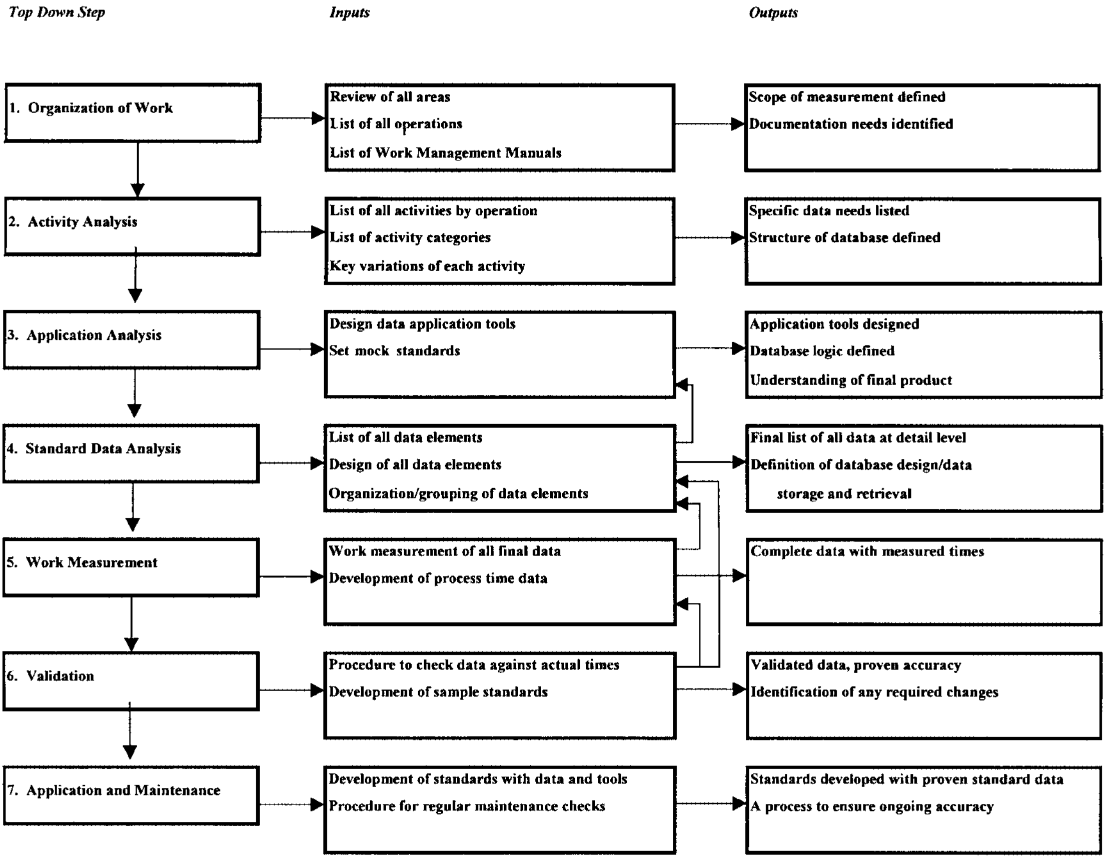

Top Down Step
Inputs
Outputs
1. Organization of Work
Review of all areas
List of all operations
List of Work Management Manuals
Scope of measurement defined
Documentation needs identified
2. Activity Analysis
List of all activities by operation
List of activity categories
Key variations of each activity
Specific data needs listed
Structure of database defined
3. Application Analysis
Design data application tools
Set mock standards
Application tools designed
Database logic defined
Understanding of final product
4. Standard Data Analysis
List of all data elements
Design of all data elements
Organization/grouping of data elements
Final list of all data at detail level
Definition of database design/data
storage and retrieval
5. Work Measurement
Work measurement of all final data
Development of process time data
Complete data with measured times
6. Validation
Procedure to check data against actual times
Development of sample standards
Validated data, proven accuracy
Identification of any required changes
7. Application and Maintenance
Development of standards with data and tools
Procedure for regular maintenance checks
Standards developed with proven standard data
A process to ensure ongoing accuracy

FIGURE 5.3.8 The seven-step top-down approach.

Activity Analysis

After determining the project scope, an information gathering process begins. Emphasis should be placed on communicating the purpose and importance of the project prior to beginning activity analysis. Typically, an activity analysis form is developed. Sample activity analysis forms are shown in Fig. 5.3.10. The form is then used as the primary tool in the information-gathering exercise. This step is required to fully understand each operation within the top from a work measurement perspective. All operations are observed and listed on the activity analysis form. Major variables of each operation are noted.

The extent of this effort will depend on the availability of information and the development team's understanding of the operation. Consideration is given to existing documentation. For example, detailed standard operating procedures or work instructions may exist that, if current, will greatly benefit the information-gathering phase. Where ISO 9000 process instructions or other detailed instructions are available, and/or where the industrial engineering group has extensive knowledge of the operation, observation and data gathering are minimized.

After completing the activity analysis for all operations, sections 2, 3, 4, 5 of the work management manual can be completed. (See excerpt examples in Fig. 5.3.11.)

1.0 Scope

The purpose of this section is to describe the types of work covered in the manual, to identify the areas in which they are performed, and to describe the products and components which are affected.

1.1 Plant Area, Department, Work Center, Cost Center
Describe where the work is performed using any or all of the above which are appropriate.

1.2 Products and Components
Describe the parts or items—giving range of sizes and/or weights; design characteristics; and any other information, such as model number or families of parts, which will help to identify the products.

1.3 Materials
List all direct materials and specification numbers which form part of the product.

1.4 Operations
List the operations that will be covered by the standard time data included in this manual. Operations which can be performed on the equipment or work stations but not covered by the data should not be listed.

FIGURE 5.3.9 Work management manual—section 1.

Application Analysis

This step involves taking a step back from the detail. The primary objective is to fully understand and design the standard data application approach. That is, once the standard data is complete, how will it be *applied* to set standards. Therefore, the emphasis of the project is changed from a detailed view of each operation to a broad view of the final result.

To determine the application approach, extensive thought must be given to design of the standards. Consideration is given to how the standards will look after completion, and how standards will be stored and retrieved. Then, you must work backwards to design the tools or systems that will be used to apply the data, resulting in standards that match the design. It is also important, at this stage, to consider the intended purpose of the standards. For example, will the standards be used for general cost estimating or staffing, or will they be used to administer an individual wage incentive plan? Over what period of time do you expect accuracy?

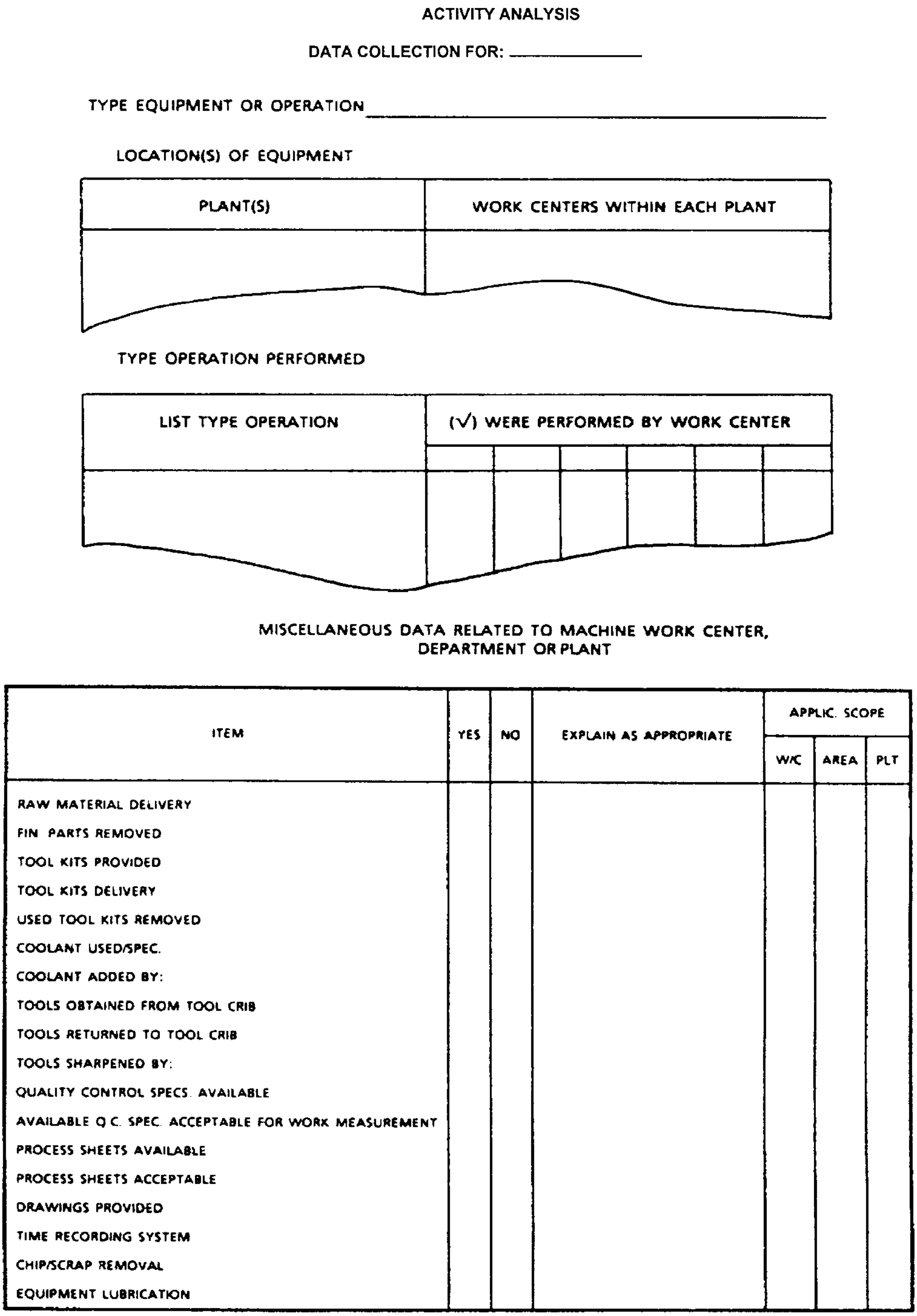
Several sample standards should be mocked up for each primary operation or area. A mock application worksheet should also be designed. The primary objective is to fully understand the requirements and develop a system design that will meet these requirements. If the application approach involves the use of expert system technology, consideration must be given to the requirements of this approach. For example, if the size of a part is a key variable in deciding what standard data to use, will the expert system have access to the data to determine part size? The reader considering an expert systems approach should read Chap. 5.9 and Chap. 12.5.

It is a common practice to develop an application worksheet or picksheet, for use in picking suboperation (level 2) data for a specific application. Several sample worksheets are shown in Figs. 5.3.12–5.3.14. (*Note:* the sample worksheets shown are completed. At this stage of development, the worksheet would be a rough draft only, without any data references.) Even where advanced (automated) data application technology is used, a worksheet is normally developed as part of the data design stage. This will help in designing the expert system logic.

Standard Data Analysis

Once the application design work is complete, the focus turns back to the detailed data. The sample worksheets, sample standards, and activity analysis forms, along with any useful

STANDARD DATA CONCEPTS AND DEVELOPMENT



ACTIVITY ANALYSIS

DATA COLLECTION FOR: ____________

TYPE EQUIPMENT OR OPERATION ______________________________

LOCATION(S) OF EQUIPMENT

PLANT(S)	WORK CENTERS WITHIN EACH PLANT

TYPE OPERATION PERFORMED

LIST TYPE OPERATION	(√) WERE PERFORMED BY WORK CENTER					

MISCELLANEOUS DATA RELATED TO MACHINE WORK CENTER, DEPARTMENT OR PLANT

ITEM	YES	NO	EXPLAIN AS APPROPRIATE	APPLIC. SCOPE		
				W/C	AREA	PLT
RAW MATERIAL DELIVERY						
FIN PARTS REMOVED						
TOOL KITS PROVIDED						
TOOL KITS DELIVERY						
USED TOOL KITS REMOVED						
COOLANT USED/SPEC.						
COOLANT ADDED BY:						
TOOLS OBTAINED FROM TOOL CRIB						
TOOLS RETURNED TO TOOL CRIB						
TOOLS SHARPENED BY:						
QUALITY CONTROL SPECS. AVAILABLE						
AVAILABLE Q.C. SPEC. ACCEPTABLE FOR WORK MEASUREMENT						
PROCESS SHEETS AVAILABLE						
PROCESS SHEETS ACCEPTABLE						
DRAWINGS PROVIDED						
TIME RECORDING SYSTEM						
CHIP/SCRAP REMOVAL						
EQUIPMENT LUBRICATION						

FIGURE 5.3.10 Sample activity analysis form.

2.0 Standard Practices and Policies

This section is used to document standard practices and policies which affect or are applicable to the work covered in the manual. It should specify those cases where the operator is responsible for following established policy and practices. The manual should not be used as a document in which all company policy and practices can be found since these are best recorded in a separate Policy and Practices Manual. The Work Management Manual need only make reference to the Policy Manual as required.

This section of the manual describes the operator's responsibility for completing the work identified in 2.1 through 2.8. This, in turn, defines what must be included in the time standards, or the allowances, or what should be excluded from the standards.

2.1 Care of Equipment and Work Area

Describe the operator's responsibility for cleaning the work area and equipment, and for the maintenance, lubrication, adjustment, and repair of machinery and equipment. Specify the frequency of those activities.

2.2 Quality Control and Inspection

Specify the operator's responsibilities for inspecting the parts or items processed. Include inspection frequencies required and the inspection criteria.

2.3 Material Service

Briefly describe how parts and materials are brought into, moved within, and carried away from the work center. Identify the operator's responsibility in this activity. If the operator has no responsibility for the material service, that fact should be noted. If the operator has material handling responsibilities, note that this time is included in the time standards.

2.4 Supply and Maintenance of Tools

Identify the operator's responsibility for getting and returning tools, and designate the tool storage area(s) for each Work Area. Describe the operator's responsibility for cleaning, repairing, adjusting, and/or reconditioning tools; and specify the frequency with which this is done.

2.5 Work Assignments

Describe how work is assigned to the operator and specify who does it.

2.6 Time and Production Reporting

Identify the operator's responsibilities for reporting run time, setup time, downtime, and production quantities. Include examples of any forms which the operator is required to use and explain their use, preferably with completed examples. Explain how time is covered for the operator to perform their responsibilities.

2.7 Setup and Tear down

Describe the responsibilities of the operator and other personnel who may be responsible for performing setup and/or tear down work.

2.8 Safety Regulations

Identify the protective clothing and safety devices required for use by the operator to comply with company, state, and federal regulations. Cover such things as the putting on and removal of aprons, masks, shields, gloves, glasses, helmets, etc. Note any required inspections or adjustments to safety devices. Specify the frequency of occurrence of each task.

2.9 Supervisor's Responsibilities

If the supervisor's responsibilities are described adequately in a Company Policy Manual or some other document, it will be sufficient to make reference to it here. The purpose of documenting supervisor responsibilities is to distinguish these from operator responsibilities.

3.0 Facilities and Equipment

The purpose of this section is to identify and locate the equipment and facilities needed to perform the work covered by this manual. You should identify and provide specifications for:
—Production Equipment
—Auxiliary Equipment
—Materials Handling Equipment
This section documents the equipment used as a basis for establishing the standard times.

FIGURE 5.3.11 Excerpts from a work management manual.

4.0 Layouts and Material Flow

The purpose of this section is to locate each Work Area within the Department or Cost Center covered by the Manual, and to describe how materials flow into, through, and out of the Work Areas. To do so, information which describes the following is needed:
—Work Area Layouts
—Department or Cost center Layouts
—Material Flow

5.0 Process Data

The purpose of this section is to describe how process times were derived. Process time is that part of an operation which is considered to be beyond the control of the operator, even though it is understood that by changing settings or adjustments on machines the operator can, in fact, influence process times. A few common examples of process time are:
—Welding Arc Times
—Spray Painting
—Heat Treating
—Machining Time, including feeds and speeds tables
—Electroplating
—Sewing (machine)

5.1 Derivation of Process Times
All mathematical calculations used (such as least squares, regression analyses, and standard deviation) should be shown. Any supporting data such as lists and tables of observed times and the method used to compile them should also be included.

5.2 Technical Processes
This section should also include a description of any special processes of a technical nature. Examples of these would be electrochemical plating, heat treating, casting and molding. Reference should be made to sources of information, such as manufacturer's manuals, technical bulletins, and reports so that these can be consulted if necessary.

FIGURE 5.3.11 Excerpts from a work management manual. (*Continued*)

work instructions, are used to develop a preliminary listing of all required work elements. A set of major activity categories is developed and defined to use in grouping the data. A sample set of activity categories and definitions is shown in Fig. 5.3.15. The data is coded by applying these categories to the list, and the list is re-sorted according to activity category. A sample form for listing data in this fashion is shown in Fig. 5.3.16. The purpose of this step is to organize the list into groups of similar tasks so that standard data can be developed to cover each group.

The data is further defined as common or unique, and this designation is added to the list. Common data must be considered across all possible areas where it will be applied, while unique data need only be measured where the unique operation occurs. Some data is constant, that is, the task is always performed using the same method, while other data is variable. When data is combined into groups as described previously, many examples of variations in similar tasks are typically uncovered.

Each activity category is then separated from the list and treated as a separate development project. The category list is further refined by adding additional qualifiers such as object, product/equipment, tool, and so on. These qualifiers allow for grouping of the data into manageable "buckets" for further analysis and will help later with storage and retrieval of the completed standard data. Each bucket of data is then reviewed and again refined to determine the measurement requirements and approach.

After listing and organizing the data requirements, statistical principles are applied to refine the lists. For example, the activity analysis might have revealed hundreds of instances of

Worksheet-Machine Operation

DATE:	VERTICAL BORING MILLS	BP NO. 52762-RH
APPLICATOR:	WORKSHEET “A”	OPER. NO. 10
APPROVED:	60” and 80” NILES	CLASS 2

LINE		ELEMENT DESCRIPTION	SETUP				EACH PIECE			
			Loc.	Unit hrs.	Occ	Total hrs.	Loc.	Unit hrs.	Occ	Total hrs.
1		Shop setup – 1st chucking	K216	.139	1	.139				
2		Shop setup – sub. chucking	K217	.116	1	.116				
	GET AND LAY ASIDE PART	O.D. I.D. HEIGHT								
3		To 36” -- To 18”					5	.042		
4		24” – 36” 18” to 48”					8	.082		
5		36” to 72” -- To 18”					7	.061		
6		To 72” Over 36” 18” to 48”					14	.082		
7		Over 72” -- To 18”					10	.070	2	.140
8		Over 72” -- To 18”					16	.091		
9		Put aside fin. mach. part					144	.031	2	.062
10	CLAMP AND TRUE	Sgl. stop – lst chucking								
11		Sgl. stop – sub. chucking	222	.328			218	.152		
12		Stop change	222	.328	1	.328	220	.105	1	.152
13		Dbl. stop – (thin section)	223	.158					1	.105
14		Forgings – 1st chucking	224	.486			227	.140		
15		sub. chucking								
16	TOOLING	Setup tool-rgh. or knife tool	197	.028			210	.019		
17		Setup tool-form or slice	221	.038			242	.029		
18		Set tool to 1st cut on surface					201	.022	12	.228
19		Set tool to add. cut on surface					202	.013	2	.058
20		Set tool to 1st cut-knife tool only					198	.020	9	.198
21		Set tool to add. cut – knife tool only					215	.005	13	.169
22		Trial cuts-tol. > ± 1/64					225	.027	6	.120
23		Trail cuts-tol. < ± 1/64					226	.055		
24		Set head to angle – normal	234	.046			234	.046		
25	GAGING	Trammel or rod	98	.025	4	.100	70	.015	4	.060
26		I.D. micrometer-to 36” dia.	181	.052			136	.034		
27		I.D. micrometer-over 36” dia	181	.052			137	.051		
28		Template or square					138	.012	2	.024
29		Calipers	187	.010	2	.020	134	.015	3	.045
30	MISC.	Change speed					207	.005	9	.045
31		Change feed					208	.003	4	.012
32		TOTAL LEVEL MANUAL TIME				.703				1.418
33		MACHINE TIME – WORKSHEET “B”				----				2.99
34		TOTAL LEVELED TIME				.70				4.41
35		% ALLOWANCE				07				.44 .60
36		TOTAL ALLOWED TIME	SETUP			.77	EACH PIECE			5.45

Note: Add process time for total operation time.

FIGURE 5.3.12 Worksheet example 1—vertical boring mills (completed).

STANDARD DATA WORKSHEET – ASSEMBLY

Section #1: General Part Placement and Handling

DESCRIPTION	USAGE PER	LOC	TMU
Gather Components and Position			
TRAVEL TO AND FROM PARTS STORAGE TO GET COMPONENT(S)	TRIP	233	*130*
GET AND PLACE EACH ITEM	1st ITEM	234	*100*
PLACEMENT OF ADDITIONAL ITEMS	ADDED ITEM	153	*60*
MOVE COMPONENT TO UNIT WITH CRANE	COMPONTENT	163	*878*
Component Alignment			
REALIGN COMPONENT ALREADY POSITIONED	OCCUR	86	*80*

Section #2: Tool Use

	INSTALL FASTENER COMPLETE				TIGHEN/LOOSEN FASTENER ONLY			
Fasteners	1st		ADDITIONAL		1st		ADDITIONAL	
HAND START ONLY FASTENER							182	*120*
PLACE WASHER/EXTRA FASTENER			188	*40*				
POWER TOOL	186	*354*	187	*244*	235	*234*	236	*124*
RATCHET	189	*410*	191	*300*	238	*290*	239	*180*
SCREWDRIVER/T-WRENCH	194	*410*	195	*300*				
WRENCH	192	*630*	193	*520*				
NUT RUNNER	A		B		C		D	
Torque	1st		ADDITIONAL		Includes Mark Torque			
GSE>20 NM TORQUE [TO 7.0 S]	199	*620*	200	*430*				
TORQUE CHECK FIRST LOC	201	*390*	202	*120*				
AUDIT TORQUE FIRST LOC	203	*874*	204	*420*				
Miscellaneous Tools	1st		ADDITIONAL					
PLIERS-GRIP	205	*200*	206	*103*				
PLIERS-CUTOFF	207	*220*	208	*110*				
PLIERS-REMOVE CAP	209	*200*	210	*90*				
HAMMER	211	*220*	212	*110*				
Surface Treat	1st		ADDITIONAL					
BRUSH LUBE-STROKE/SQ. IN.	213	*160*	133	*50*				
DIP OBJECT IN GREASE			120	*20*				
APPLY TAPE (PER STRIP)	214	*210*	215	*100*				
REMOVE TAPE (PER STRIP)			150	*190*				
STAMP ASSOCIATE ID	166	*140*	167	*20*				
WIPE SURFACE PER ½ SF	242	110	243	50				
Read	1st		ADDITIONAL					
READ VIN#			216	*132*				
READ LOT CONTROL NUMBER			217	*132*				
LOOK UP DATA IN TABLE			222	*190*				
READ BROADCAST SHEET			230	*254*				
READ DATE/TIME			237	*60*				
SCAN BAR CODE	240	70						
Write	1st		ADDITIONAL					
WRITE TORQUE	218	*270*	219	*150*				
WRITE ASSOC. NUMBER	220	*230*	221	*110*				
WRITE VIN NUMBER	223	*350*	224	*230*				
WRITE LOT CONTROL NUMBER	225	*430*	226	*310*				
WRITE DATE/TIME	227	*350*	228	*230*				

Inspect	PER OCCUR.	
INSPECT 1 POINT	97	*10*
FEEL FOR DEFECT	98	*100*
INSPECT/VERIFY FUNCTION	231	*60*
CHECK GAP/CONTOUR	229	*130*
Operate	PER OCCUR.	
PUSH BUTTON/CYCLE PRESS LEVER – PUSH/PULL	145	*30*
ACTIVATE AGV TO ADVAN	162	*62*
P-TIME (1 SEC)	185	*28*
ROTATE FIXTURE	181	*112*
OPEN/CLOSE CLAMP	134	*50*
Assemble by Hand	PER OCCUR.	
INSTALL/REMOVE SNAP	153	*60*
TIE STRAP	159	*150*
REMOVE TIE STRAP	151	*120*
ROUTE CABLE PER DIR	232	*30*
INSTALL GROMMET	132	*210*
CONNECT PLUG-IN	146	*100*
INSTALL SPRING	135	*190*
INSTALL SEAL (PER FOOT OR CORNER)	149	*120*

Section #3: Job Preparation

JOB PREPARATION	LOC	TMU
OPEN BOX, DISCARD SCRAP (Box on Skid)	164	*1450*
OPEN BOX, DISCARD SCRAP (No Skid)	165	*1970*
GET IN & OUT OF CAR	175	*420*
OPEN & CLOSE DOOR	241	*160*

HOSE ASSEMBLY		
WITHIN REACH	LOC	TMU
HOSE 12-50 MM	119	*450*
DIP IN LUBE	120	*20*
CLAMP TO HOSE	121	*90*
PWR TIGHTEN CLAMP	122	*110*
SM HOSE > 12 MM	158	*60*

Definitions

1st FASTENER COMPLETE:	Place and start fastener, get tool, place tool, use tool, aside tool
ADD'L FASTENER COMPLETE:	Place and start fastener, place and use tool
TIGHTEN/LOOSEN 1st FASTENER:	Get tool, place tool, use tool, aside tool
TIGHTEN/LOOSEN ADD'L FASTENER	Place tool, use tool

FIGURE 5.3.13 Worksheet example 2—assembly.

Shape/Rout Worksheet

SETUP/ADJUST

Take Fence on/off	:234:	Adjust Fence	:243:	Set T-Square Fence	:134:
Take Table Shim on/off	:356:	Tagout/Untag Machine	:174:		
Change Router Bit	:134:	Change Head on Chisel	:145:		
Change Head with or without Bearing	:175:	Adjust Speedfeed or Head Height	:154:		
Adjust Guidepin Height	:123:	Adjust Guidepin Horizontal	:324:		
Setup Pattern	:145:	Remove Banding	:152:		

PREPARE/REPORT

Read Paperwork	:158:	Prepare Paperwork	:123:	Prepare Tally Sheet	:235:
Write Checkmark	:143:	Prepare and Report Defects	:269:		

MOVE

Move Material (object, cart, material, stack or part)

Within Reach w/o bends	:166:	Within Reach w/ bends	:149:

With Steps	(1-2)	(3-7)	(8-15)	(16-33)	(34-57)	(58-102)	(103-191)
	:256:	:257:	:258:	:259:	:260:	:261:	:262:

Turn Small Part	:153:	Large/Bulky Part	:164:	Select & Return Pattern	:334:

LOAD/UNLOAD

	(within reach)				(1-2 steps)	
	without bend			with pbend	without bend	with pbend
Description	w/o *fence*	w/ *fence*	w/ or w/o *fence*	w/ or w/o *fence*	w/ or w/o *fence*	w/ or w/o *fence*
Load one part	:101:	:105:	-------	:102:	:103:	:104:
Load several w/adj	-------	-------	:106:	:107:	:108:	:109:
Load sev. w/o adj	-------	-------	:110:	:111:	:112:	:113:
Unload one part	-------	-------	:106:	:107:	:108:	:109:
Load & Unload one	-------	-------	:114:	:115:	:116:	:117:
Load & Unload sev.	-------	-------	:118:	:119:	:120:	:121:
Secure Part with one clamp	:131:	w/ two		:133:	w/ three	:135:

OPERATE

Start & Stop One Button Machine	:194:	Multi-Button Machine	:299:
Activate Machine/Foot Pedal (hold)	:199:	w/ in reach	:288:

ASSEMBLE

Secure Material with tape or string	:376:	w/ handbander	:377:

PROCESS DATA

S	Speed/Length	10.5	11.0	14.5	20.0	24.0	
P	----------------	-----	-----	-----	-----	-----	
E	8.50	172	180	237	327	392	
E	12.50	117	122	161	222	267	Times in
D	13.00	112	118	155	214	256	TMU
F	15.00	97	102	134	185	222	
E	19.25	76	79	105	144	173	
E	30.25	48	51	67	92	110	
D	38.00	38	40	53	73	88	

SURFACE TREAT

Putty Void	:353:	Clean Face and Back	:349:
Sand for Defect	:378:	Sand Plywood	:391:

FIGURE 5.3.14 Worksheet example 3—woodworking.

Spray Lubricant Per Sq. Ft.		:384:		Wax Surface Per Sq. Ft.	:343:
Scrap Glue Per Panel		:341:			
------INSPECT------					
Inspect One Place with Thickness Gauge		:349:		Additional Places	:387:
Inspect by Feel or Under Light		:333:		Inspect One Point	:323:
Measure One Point with Tape or Rule		:385:		Additional Points	:122:
Measure with Caliper	:312:	Count Part	:322:	Select Face	:371:
------MARK------					
Mark Defect		:339:		Mark Checkmark with Crayon	:393:

FIGURE 5.3.14 Worksheet example 3—woodworking. (*Continued*)

"load part into machine," while statistical analysis of these occurrences, after grouping and review, might indicate that only a few standard data elements are required to provide statistically accurate measurement.

Since standard data is normally designed for wide use, it is important that thorough and detailed application instructions be written for the data. These instructions will become part of the data and should also be included, to the extent required, on the application worksheets. An example of the type of instruction normally required in shown in Table 5.3.1.

The standard data analysis phase will also help in choosing a measurement approach based on the accuracy requirement of a particular set or subset of data. Some data sets may require

ACTIVITY	
Assemble	Join or fit together parts or materials into a single unit. Examples: assemble, apply, install
Inspect	To examine carefully and critically for defects in fit, finish and specifications. Examples: count, inspect, measure, select, identify
Load/Unload	Obtain, place and secure an item on a machine or fixture, and/or remove and aside an item from a machine or fixture. The item may be material, part or fixture. Examples: load, unload, position
Mark	Writing or marking on any material or product. Excludes paperwork. Examples: scribe, mark, write, outline
Move	Moving items within or between work areas excluding loading and unloading machines. Examples: stack, move, turn, transport
Operate	Activate, engage or disengage equipment before or after a process time. It does not include the process time. Examples: operate, start, stop, start/stop
Prepare/Report	Reading, writing and handling any paperwork required to begin, complete or report production. Examples: read, write, make ready
Setup/Adjust	Setup work area, equipment and materials, for start-up. Make adjustments as required for continuous production. Examples: adjust, change, lube, replenish, setup, lockout
Surface Treat	Improve finish of material or part. Examples: sand. clean, scrape, spray, stain, repair, polish

FIGURE 5.3.15 Activity categories and definitions.

Description/Title	Activity	Object	Tool	Size/ Capacity	Work Area	Common /Unique	Constant/ Variable	Notes	Data Locator Number	Data Filed
Assemble 2 parts at bench with threaded fasterners	Assemble	Part	Hand	Small	Bench	Common	Constant	applies to hand carried parts only		
Attach bracket at line (hand tight) with 4 bolts	Assemble	Part	Hand	Small	Line	Common	Variable			
Attach part at line with 3 bolts, nuts and washers	Assemble	Part	Hand	Medium	Line	Common	Variable			
Attach part at bench with 2 bolts, nuts	Assemble	Part	Hand	Small	Bench	Common	Variable			
Atttach cable to bracket at line with one wingnut	Assemble	Cable	Hand		Bench	Unique	Constant	data is unique to this operation		
Attach part to fixture with one bolt	Assemble	Part	Air Wrench	Small	Machining	Common	Variable			
Attach part to fixture with two bolts	Assemble	Part	Air Wrench	Small	Machining	Common	Variable			
Install wheel to assembly with special tool	Assemble	Wheel	Special	Large	Line	Unique	Constant	data is unique to this operation		
Inspect torque setting on 4 bolts	Inspect	Part	Torque Wrenc	Medium	Line	Common	Variable	includes use of torque wrench		
Inspect torque setting on 3 nuts at bench	Inspect	Part	Torque Wrenc	Small	Bench	Common	Variable	includes use of torque wrench		
Inspect gap between bracket on sub-assembly	Inspect	Part	Special		Bench	Common	Constant			
Visually inspect surface finish on part	Inspect	Surface		Small	Machining	Common	Variable			

FIGURE 5.3.16 Data listing form.

TABLE 5.3.1 Data Application Instructions

Location	Description	Application instructions
1	Get and load piece in fixture with hoist and secure.	Apply only to pieces handled with a hoist. Includes frequency of application = once per piece loaded. Do not apply where powered crane use is required.
2	Get and load piece in fixture by hand and secure.	Apply to pieces between 15 and 60 lbs. Do not apply to pieces where hoist use is required. Frequency = once per piece.
3	Get, load, and secure piece in universal vise.	Apply only to use of universal vise. Do not apply to loading parts in fixtures, or where use of a hoist is required. Frequency = once per piece.
4	Load 2 parts in fixture by hand.	Apply to loading part by hand only, where 2 parts are loaded at once. Do not apply where use of a hoist is required. Frequency = ½ per part.

accurate measurement, while estimates may be sufficient for others. Now that all data requirements have been clearly defined, the standard data can be developed. This final step (standard data analysis) prior to the actual application of work measurement is critical in achieving useful, well-defined data.

Using Statistics to Determine Suboperation Times

When developing standard data, it is typical to find an activity where the time required is not one precise time, but a range of times. The methods followed and the times required may vary depending on part weight or dimensions, distances moved, tools used, or fasteners used. Considerable time can be invested in developing detailed standard times for each identifiable method. Developing so many standard times not only wastes development time, but the application of different standards for such variations can be impractical. Rather than developing a large number of time values, standard data groupings or "slots" can be developed.

By identifying the range of times covering the probable extremes of the activity being measured, it is possible to determine statistically how many standard time values (slots) are needed to cover that range of time. It is then possible to determine the number of standards needed and identify the maximum allowable time range covered by a standard, and still preserve the required accuracy.

For example, assume that standards are required for setting up a machine where the standard time can vary from 6 to 30 minutes. It is possible to classify these setups into time groupings, but how many classifications are needed? How large can the time increments between standards be and still preserve the needed accuracy?

Another case is a material handling activity where the storage location and distances traveled vary depending on the congestion, available rack space, or type of product. If the time per trip can vary from 1 to 10 minutes, how many separate delivery standards are needed to provide ±5 percent accuracy over a calculation period? Can a weighted average be used for all trips? Is it necessary to identify many different locations and apply a separate standard for each location? What is the minimum number of standards required to cover the total range and still preserve ±5 percent accuracy?

The accuracy required for most industrial applications is ±5 to 10 percent for the time period over which performance is calculated. The calculation period is usually either an 8-hour period or a 40-hour period.

To calculate the accuracy required of an individual standard or *percentage allowed deviation,* the following formula can be used:

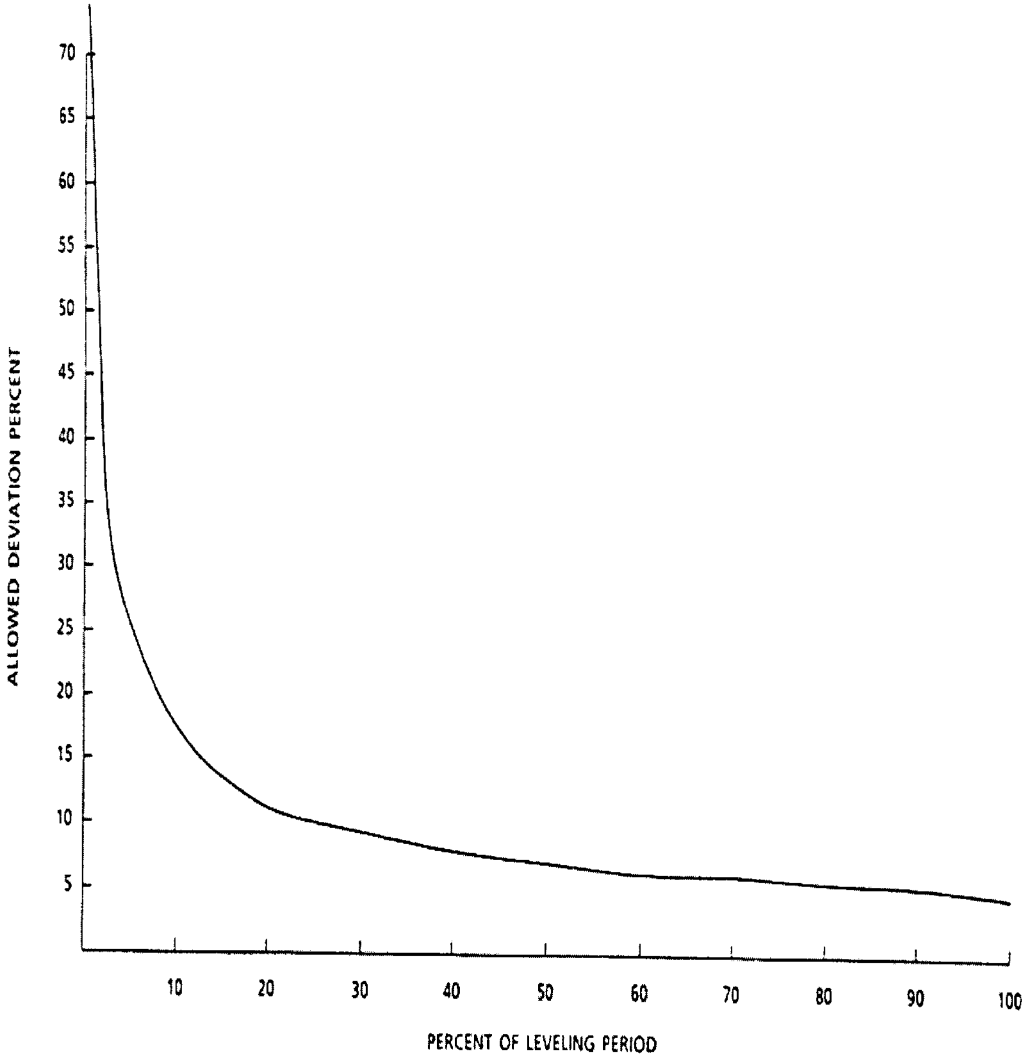


FIGURE 5.3.17 Allowed deviation based on leveling period.

$$r_t = \pm r_T \sqrt{\frac{T}{n \times t}}$$

where r_t = (percent) allowed deviation for a suboperation or standard
r_T = required accuracy (usually ±5 percent or ±10 percent) for the calculation period
T = time period required for the accuracy level to be reached (calculation period)
n = number of occurrences of the measured activity over the calculation period
t = standard time for the measured activity (suboperation)

Applying the formula for a measured activity that takes 0.2 standard hours and occurs once per 8-hour period, the allowed deviation for that one activity standard can be calculated as follows:

$$r_t = \pm 0.05\sqrt{\frac{8}{1 \times 0.2}} = 0.32 \text{ or } \pm 32\%$$

This means that one standard (0.2 standard hours) can be applied to cover variations in work content of ±32 percent and still maintain ±5 percent accuracy in the result of an 8-hour time period calculation:

$$0.2 + 32\% = 0.264$$

$$0.2 - 32\% = 0.136$$

In this case, a time value of 0.2 standard hours can be used to cover activities ranging in required time from 0.136 to 0.264 standard hours.

The same formula can be applied to an individual time value, or a range of time to determine standard data slot values. For example, to determine the number of standards needed to cover the variation from 0.20 to 0.5 hour with a frequency of 2 per 8-hour day, and required accuracy of ±5 percent, acceptable time groupings or slots of time can be identified as follows:

- *Calculate the allowed deviation for 0.20 hour.*

$$r_t = 0.05\sqrt{\frac{8}{2 \times 0.20}} = +0.224 \text{ or } 22.4\%$$

$$0.20 \times 0.224 = \pm 0.045 \text{ standard hour allowed deviation}$$

- *Calculate a time range.* If 0.2 hour is the minimum time needed, the time range should be a range where 0.2 hour is 0.045 standard hour below the average and the top of the range is 0.045 standard hour above the average. The range in this case would be

  0.2 minimum time for the range

  0.2 + 0.045 or 0.245 for the average of the range

  0.245 + 0.045 or 0.290 for the top of the range

Thus, the time range for the first slot is .200 to .290. The remaining slots are determined as shown:

		Standard time range, standard hours	Allowed standard for the range, standard hours (mid point)
Slot #1			
$r_t = 0.05\sqrt{8/2 \times 0.20}$	$= 0.224$ or $+ 22.4\%$	0.200–0.290	0.245
Allowed deviation	$= 0.2 \times 0.224 = 0.045$		
Bottom of range	$= 0.20$		
Middle of range	$= 0.20 +$ dev. 0.045 $= 0.245$		
Top of range	$= 0.245 +$ dev. 0.045 $= 0.290$		
Slot #2			
$r_t = 0.05\sqrt{8/2 \times 0.290}$	$= +0.186$ or $+ 18.6\%$	0.290–0.398	0.344
Allowed deviation	$= 0.29 \times 0.186 = 0.054$		
Bottom of range	$= 0.290$		
Middle of range	$= 0.29 + 0.054 = 0.344$		
Top of range	$= 0.344 + 0.054 + 0.398$		

Slot #3		
$r_t = 0.5\sqrt{8/2} \times 0.398$	$= +0.159$ or $+ 15.9\%$	0.398–0.524
Allowed deviation	$= 0.398 \times 0.159 = 0.063$	
Bottom of range	$= 0.398$	
Middle of range	$= 0.398 + 0.063 = 0.461$	
Top of range	$= 0.461 + 0.063 = 0.524$	

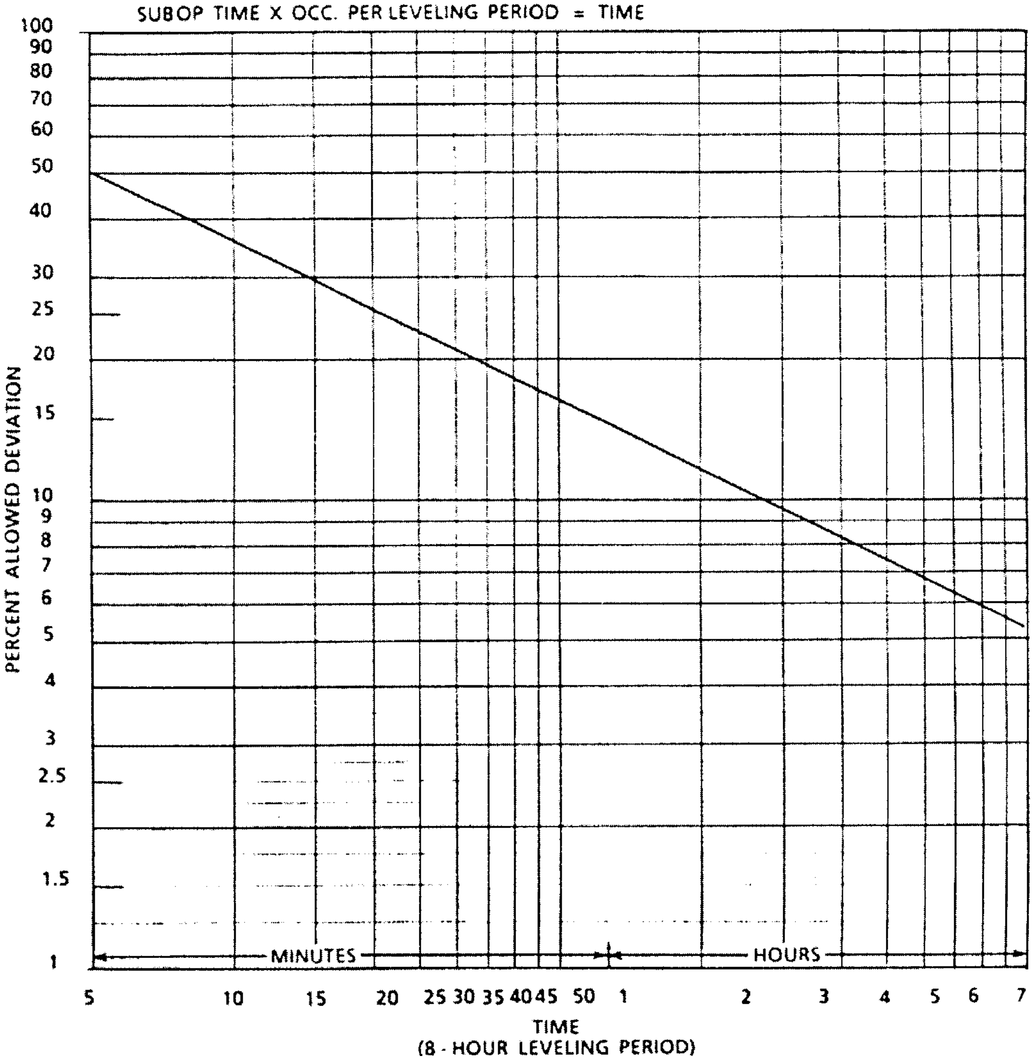


FIGURE 5.3.18 Percent allowed deviation based on 8-hour leveling period.

STANDARD DATA CONCEPTS AND DEVELOPMENT

After determination of the number of time slots needed and the standard time for each slot, a representative method (or benchmark) illustrating the activities covered by the standard can be developed. All identifiable variations in the activity can be slotted into those three time groupings. This is typically done based on the primary variable(s) that is driving the difference in time.

Figure 5.3.18 is a simplified chart showing the allowed deviation formula, based on an 8-hour calculation period. To use this chart, multiply the standard time per occurrence by the expected frequency per 8-hour period to get the time figure then find this figure on the scale at the bottom of the chart. Find the point on the line directly above and move to the left to locate the percent allowed deviation.

Standard Data Development

At this point the logic of the top-down approach should become very apparent. All operations within the defined top have been reviewed, and work elements have been consolidated based

---

TIME STANDARD VALIDATION OBSERVATION FORM

DATE ____________

DEPARTMENT ____________

MACHINE/WORK CNTR ____________

PART INFORMATION ____

OBSERVATION NOTES ____

____

START TIME ____________

NO. OF CYCLES OBSERVED ____________

STOP TIME ____________

EXCEPTIONS/ADJUSTMENTS ______________________________________

ALLOWANCE ITEMS ____

____

NOTES ____

____

NET OBSERVED TIME ____________

PERFORMANCE RATING (circle one) 85 90 95 100 105 110 115

METHOD LEVEL RATING (circle one) 85 90 95 100 105 110 115

LEVEL OBSERVED TIME ________net observed x method level x perf. rating

RATING NOTES ____

____

STANDARD TIME CALCULATION

STANDARD TIME ____

STANDARD WORK NOT OBSERVED ____

____

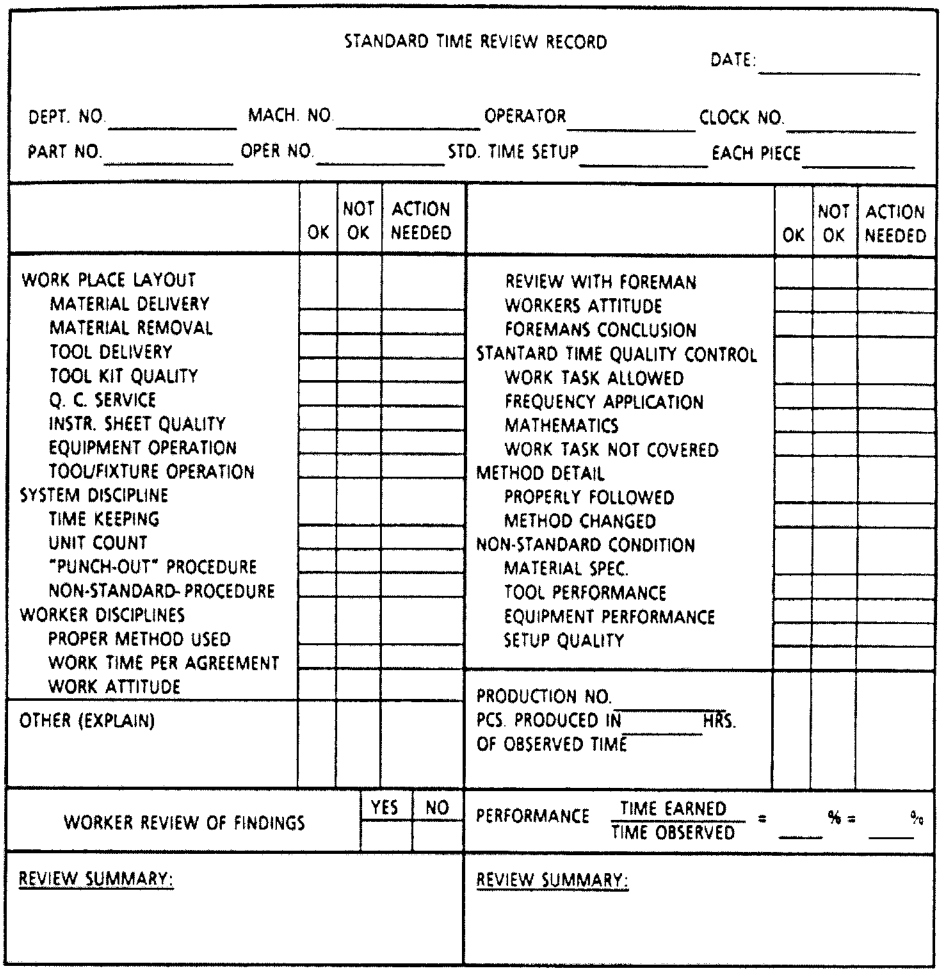
STANDARD TIME NOT OBSERVED ____________

NET STANDARD TIME ____________

FIGURE 5.3.19 Sample validation form (1).

on commonalities. A standard data structure has been designed that will provide accurate coverage of all operations, once the data is applied to the operations, using a minimal number of descriptively titled and organized elements. The advantages in terms of development effort, application effort, and consistency should be obvious. Although some rough measurement was likely required to complete the standard data analysis, it is important to note that no final measurement has been completed to this point. With top-down standard data, the investment is in the design rather than the actual measurement.

Extensive data design efforts have resulted in a very clear definition of exactly what needs to be measured to achieve a complete set of standard data. A final set of data is then developed to cover the requirements of each category. Again, the data could be developed using a number of techniques (including PMTS application, time studies, or even estimates) and, as explained earlier, accuracy requirements play a role in determining the technique. Final process time data should also be collected at this point, and application tools and worksheets are finalized by adding the completed standard data. Refer to Chap. 5.1 for more information about work measurement systems.



STANDARD TIME REVIEW RECORD

DATE: ______________

DEPT. NO. ____________ MACH. NO ____________ OPERATOR ____________ CLOCK NO. ____________

PART NO. ____________ OPER NO ____________ STD. TIME SETUP ____________ EACH PIECE ____________

	OK	NOT OK	ACTION NEEDED
WORK PLACE LAYOUT			
MATERIAL DELIVERY			
MATERIAL REMOVAL			
TOOL DELIVERY			
TOOL KIT QUALITY			
Q. C. SERVICE			
INSTR. SHEET QUALITY			
EQUIPMENT OPERATION			
TOOL/FIXTURE OPERATION			
SYSTEM DISCIPLINE			
TIME KEEPING			
UNIT COUNT			
"PUNCH-OUT" PROCEDURE			
NON-STANDARD- PROCEDURE			
WORKER DISCIPLINES			
PROPER METHOD USED			
WORK TIME PER AGREEMENT			
WORK ATTITUDE			
OTHER (EXPLAIN)			

	OK	NOT OK	ACTION NEEDED
REVIEW WITH FOREMAN			
WORKERS ATTITUDE			
FOREMANS CONCLUSION			
STANTARD TIME QUALITY CONTROL			
WORK TASK ALLOWED			
FREQUENCY APPLICATION			
MATHEMATICS			
WORK TASK NOT COVERED			
METHOD DETAIL			
PROPERLY FOLLOWED			
METHOD CHANGED			
NON-STANDARD CONDITION			
MATERIAL SPEC.			
TOOL PERFORMANCE			
EQUIPMENT PERFORMANCE			
SETUP QUALITY			
PRODUCTION NO. ____________ PCS. PRODUCED IN ____________ HRS. OF OBSERVED TIME			

	YES	NO
WORKER REVIEW OF FINDINGS		

PERFORMANCE $\frac{\text{TIME EARNED}}{\text{TIME OBSERVED}}$ = ______ % = ______ %

REVIEW SUMMARY:

REVIEW SUMMARY:

FIGURE 5.3.20 Sample validation form (2).

Validation

The final development step is validation: testing the data for accuracy, coverage, and ease of application, and making any necessary adjustments. This step is critical since a general set of data will now be widely used. It is important that the data be thoroughly tested. The application tools/worksheets should be used to test the application of the data in each area. Sample standards are set using the worksheets, and the methods and prescribed work conditions are checked against actual conditions. This approach will test not only the accuracy and coverage of the data but also the ease of application using the worksheets or other application tools. Any missing data is added, and any required fine-tuning of the application tools is completed. It is important to note that while actual times are collected for the purpose or comparison, this is done to provide a test of reasonableness. That is, standard data is not arbitrarily changed as a result of validation studies. Sample validation forms are shown in Figs. 5.3.19 and 5.3.20. At this point, sections 6, 7, and 8 of the work management manual should be completed. (See excerpt in Fig. 5.3.21.)

While communication and involvement is important throughout the standard data development process, the validation stage presents a good opportunity to increase involvement. Since the data is moving from a development mode to actual application, involvement opportunities abound. Involving supervisors and workers in the validation will help sell the concept and increase confidence.

6.0 Manual methods

The purpose of this section is to provide a general description and primary sequential steps that a worker will follow in performing the operation. This section provides in a summary format the work activities that the worker is expected to perform and for which a standard time will be allowed.

This section is not intended to provide a detailed method description on how to produce the variety of operations for which standard times can be established from these standard data.

7.0 Standard Time Calculation

This section describes how to set a standard. It will include the use of:
—Worksheets
—Direct Read Tables and Charts
—Spreadsheets and Standard Time Groupings (where appropriate)
—Expert System Logic

7.1 Worksheet, Tables, Charts
Include one copy of each of the above needed to set standards on all the work covered in the Manual.

7.2 How to Calculate Time Standards
Provide detailed instructions describing how to set time standards. Include completed examples of worksheets and individual time standards calculations to cover each type or class of work in the Manual.

8.0 Standard Data Backup

This section will contain all the data and supporting information used in developing the standard time calculations in Section 7. This will include all elements, constants, sub-operations, and combined sub-operations. motion pattern analysis (MOST, MTM, or basic time study elements), the synthesis is included. This represents the minimum acceptable level of methods documentation.

FIGURE 5.3.21 Work management manual excerpt.

Application and Maintenance

Now that all data has been developed and tested, it can be made available for application. Normally, an initial period of developing standards for many operations is completed. The effort then moves into a maintenance mode, where standards are set as needed for new operations or products, or when methods and processes change. Actual application may be manual, by having someone select data from a worksheet or picksheet, or highly automated, where expert system logic has been developed. Readers unfamiliar with the expert systems

9.0 Allowances

Allowances fall within two categories:

9.1 Regular—These are intended to cover time for personal needs, time for rest to overcome the effects of fatigue or monotony, time lost due to unavoidable delays, and loss of incentive opportunity (as in process time).

9.2 Special—These will cover conditions not normally encountered, such as extreme heat or cold, smoke, paint spray or fumes, and the use of restrictive clothing and equipment, to mention a few.

Specify the type of allowance, what it is intended to cover, and the percentage. State the authority by which the allowance is given, such as a Contract or Agreement, or if by company policy. If the allowances were developed by work sampling or some other type of study, include the supporting data in this section; or if a separate study, identify the source. One example covering the application of allowances should be included in this section.

If an allowance policy exists, reference should be made to the source of the allowances.

10.0 Maintenance

If it is essential to include all important information in a manual, it is equally important to maintain it in an up-to-date condition. Changes in equipment, methods, and working conditions occur frequently; they create the need for revising the material contained in the manual. It is therefore necessary to provide an effective means for ensuring that all revisions are made in a timely manner and that they are promptly disseminated to all users.

10.1 ***Responsibility for Maintaining Standards.*** It is the responsibility of the manager of the industrial engineering department to ensure that all copies of the work management manual are maintained in a complete and up-to-date condition. When any condition changes which might affect the contents of the manual or the calculation of time standards, the industrial engineering department will review the change to determine what effect, if any, it will have on the manual or on time standards. Where warranted, the necessary revisions will be made and submitted to the manager of the industrial engineering department for approval.

10.2 ***Distribution.*** This section is to provide a record of the work management manual distribution within the company or other divisions of the company, in accordance with the following control sheet format.

Copy No.	Division	Issued to (name and dept.)	Date

FIGURE 5.3.22 Work management manual excerpt.

10.3 ***Revisions.*** The maintenance of the work management manual is important to assure the continuity and accuracy of the data. It is therefore necessary to keep a record of the revisions made, not only for maintenance of the data but also to satisfy a contractual agreement with the union related to standard changes. It is suggested that the following format be used to record the revisions made in sufficient detail to support standards adjustments.

Date	Change description	Approval
________	________________	________
________	________________	________

Section 10 as described may be part of the industrial engineering department policy manual and need not be repeated in a work management manual. However, reference should be made to the appropriate policy manual covering standard data maintenance procedure.

FIGURE 5.3.22 Work management manual excerpt. (*Continued*)

approach would benefit from reading Chap. 5.9 and Chap. 12.5. Where manual data selection is used, the results are typically entered into a computerized standards software program. This type of software is described in Chap. 5.6. The actual process of setting standards also involves the application of allowances. The development and use of allowances is thoroughly described in Chap. 5.5.

At this point, sections 9 and 10 of the work management manual can be added (see Fig. 5.3.22). The work management manual should now include everything required to support the data.

FUTURE TRENDS

The future of work measurement, like anything else, is uncertain. It is likely that, as the U.S. economy continues to shift toward high technology and the reliance on manual labor decreases, work standards will receive less attention. The author believes that organizational support for standards will continue to decrease in the future. Needs in this area will continue to be looked at, at least in the United States, with more and more scrutiny, and elaborate systems for standards and endless measurement will not be funded.

However, the need to have standards will still be present. Experience has proven that measurement and standards are essential to efficient and productive operation and effective decision making. This will not change in the foreseeable future. Customized products and highly flexible work environments will dominate. Lean manufacturing will become commonplace, and companies will learn to focus on efforts that will result in a true impact on the overall systems. Wage incentives will continue to evolve to be based on broader organizational goals.

If this is the future, then the future will be even more dependent on well-conceived standard data systems. With constantly changing products, processes, and systems, the need will exist for logically packaged, easily applied measurement data. Standard data fits this need perfectly.

Success with standards in the future will require looking at only what is critically important. The successful industrial engineer who can determine what is important to measure will be prepared to fill this need with well-designed standard data.

CONCLUSION

Developing standard data is a challenging task. The concept is easy to understand and is commonly applied throughout many industries. However, the discipline required to develop work measurement standard data is not widely practiced. For many, experience has been a poor teacher. The use of standard data results in many benefits, but there are also limitations. By following the principles and concepts presented here, the industrial engineer can successfully develop and use standard data. The result of successful development will be benefits reaped for many years. The future of work measurement will be highly dependent on standard data.

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BIOGRAPHY

John Connors is a consulting manager and shareholder at H. B. Maynard and Company, Inc., in Pittsburgh, Pennsylvania. Since joining Maynard in 1990, he has held positions of consultant, senior consultant, and consulting manager. Prior to joining Maynard, he was employed as a CNC programmer and machinist for an OEM machining company. John has a bachelor of science degree in industrial management–manufacturing from California University of Pennsylvania.

Source: MAYNARD'S INDUSTRIAL ENGINEERING HANDBOOK

CHAPTER 5.4

DEVELOPING ENGINEERED LABOR STANDARDS

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Labor standards have been common throughout industry since the dawn of the Industrial Revolution, and have been traced back to the ancient Egyptians. Today, engineered standards, based on specified methods and work conditions, are used to manage by fact and help plan effectively, determine costs, and manage performance. The procedure to develop and calculate standards has been studied and refined, leading to a more efficient and practical approach. Provided that realistic accuracy and economic requirements have been established, it is possible to establish standards for any type of work in any industry where methods and work conditions can be defined. Accuracy is a function of work conditions, while economic concerns are a function of the measurement system and its application. Every labor-intensive organization can benefit from labor standards. In the past, many manufacturing companies have used standards to plan effectively, determine costs, and measure and pay for performance. Today, however, the door is wide open to the proper and efficient use of labor standards in a majority of industries.

This chapter will describe the specifics of developing engineered labor standards for different types of operations. The focus is on defining a standard and its components, describing benefits and uses of standards, and explaining the development process. For all work that can be measured, this text will help outline the specific nature of the standard development process in different arenas and provide examples from which the industrial engineer can learn and apply.

INTRODUCTION AND HISTORY OF STANDARDS

Prior to the Industrial Revolution, labor was cheap and readily available. This labor surplus led to little, if any, interest in the measurement of work. If more output was needed, more people were added to fill the void. However, the introduction of electricity and steam power along with many other inventions led to numerous production factories and the birth of the Industrial Revolution. Labor shortages developed, accompanied by the rise of labor rates. Competition increased as new organizations were formed. With the work of Frederick Taylor, Henry Gantt, Frank and Lillian Gilbreth, Harrington Emerson, and others came the birth of scientific management and the principles of organization, methods, and work management that today constitute a large part of industrial engineering. Labor productivity and measurement of work became concerns because adding more labor was no longer the best option. Instead, understanding a fair day's work and defining the best way to perform a task led to the measurement of work and development of labor standards. Work measurement became a major role for the industrial engineer. With the advent of time standards developed by estimation, historical data, time study, and predetermined motion time systems, the following definitions and information can be used to develop labor standards. With the introduction of various predetermined time systems to cover a wide range of operations, and the introduction of computers to calculate work measurement, today these principles can be applied effectively in many organizations.

DEFINITIONS, USES, AND BENEFITS OF STANDARDS

Definitions

Webster's Dictionary defines a *standard* as "something that is set up and established by authority as a rule for the measure of quantity, weight, extent, value, quality, or time." The formal definition of a *time standard,* as provided by the American National Standards Institute (ANSI), is given here:

> A unit value of time for the accomplishment of a specific work task as determined by the
>
> **a.** Proper application of appropriate work measurement techniques by qualified personnel, and
>
> **b.** Generally established by applying appropriate allowances to the normal time.

A time standard is often misunderstood by many of the people who are directly affected by it. A definition that promotes a better understanding of time standards is as follows:

> An *engineered labor standard* is the total allowed time that it should take for an average skilled and well-trained operator working at a normal pace to perform an operation including manual time, process time, and allowances, based on established and documented *work conditions* and a specified work *method.*

The key here is that engineered standards are methods based, and represent the time to perform an operation under defined work conditions while working at a normal pace. The backup necessary for engineered standards includes documented conditions such as layout, tooling, machines, equipment, and expected results. In addition, the method that is measured must match the method that is performed. The time can be developed using one of several systems such as MOST, MTM, or standard data.

Based on the previous definition, the following equation takes form for a specified operation:

$$\text{Manual Time} + \text{Process Time} + \text{Allowances} = \text{Time Standard}$$

Further broken down, this yields:

$$\text{Manual Time} + \text{Process Time} = \text{Normal Time}$$

$$\text{Normal Time} + \text{Allowances} = \text{Time Standard}$$

By breaking a time standard into its three components, manual time, process time, and allowances, and introducing normal time as a subset of a standard, each of these in turn must also be defined.

Manual time is the time required to complete a defined element of work done by hand or with the use of tools or assists, and is not controlled by a process or machine. The manual time in an engineered labor standard is established based on the following:

- Average skilled and trained operator
- Normal pace
- Prescribed specific method
- Defined expected results
- Specified tools, materials, and layout

The manual time must be determined by the proper application of an appropriate work measurement technique by qualified personnel. The following five steps summarize how the manual time is determined:

1. Analyze and document the method.
2. Identify the best method.
3. Break the method down into elements.
4. Assess a time to each element.
5. Reassemble the elements into an operation.

Process time is the time that is controlled by electronic or mechanical devices or machines rather than being manually controlled. This component represents either the time that a machine is running or the time that a process is occurring to fabricate, manipulate, assemble, or otherwise alter a product or part. The time is based on a machine's speed and feed rates or the amount of time that a product remains in process. When machines are involved, the speed must be validated from actual observation and measurement or engineering calculation. Where processes are involved, the time a product remains in the process is established by time study (see Chap. 17.2) and must be validated.

Process time is established by defining the parameters of the process and then determining the time. First, define the beginning of the process, which may be initiated by pushing a button, loading a part, and so forth. Next, define the end of the process, which may be the end of a machine cycle, or a manual interaction to unload. Finally, assess the time required using time study, computer numerical control (CNC) programs, or an engineering calculation based on output to determine the process time.

Allowances are the time added to the normal time to account for personal time, rest time, and minor unavoidable delays by multiplying it by an allowance factor [1 + (allowance time / total productive time)]. Since allowances are discussed extensively in Chap. 5.5, this topic will not be further examined here.

In addition to these definitions, use of the following terms when measuring work will facilitate understanding and consistency:

> A *suboperation* is a discrete, logical, and measurable part of an operation or time standard. Suboperations are often referred to as building blocks, or portions of work. The content of a suboperation may vary depending on type of operation, accuracy requirements, and application area. The work measurement application and standard-setting process is simplified through the use of these measured fractions of work.
>
> An *operation* is the intentional changing of an object in any of its physical or chemical characteristics; the assembly or disassembly of parts or objects; the preparation of an object for another operation, transportation, inspection, or storage; or the planning, calculating, or giving and receiving of information.
>
> A *process plan* is a grouping of one or more operations that represents a more general entity. The work usually occurs at several workplaces or even an entire facility. This covers

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a range of work and usually consists of both setup and run activities. Process plans are also referred to as *routers* or *routings.*

Internal in the realm of work measurement refers to the method and time of a motion, suboperation, or operation occurring at the same time or during another motion, suboperation, or operation. Since the work can be performed simultaneously, the method should be documented, but no additional time should be included in the standard for internal work.

External therefore is the opposite of internal. All work that is performed nonsimultaneously, be it a motion, supoperation, or operation, is considered external. The work cannot be performed at the same time as any other work. Time for external work is included in the standard.

Uses and Benefits

There are many common and practical uses and benefits of engineered labor standards. Generally, standards are used in one or more of the following three ways to directly or indirectly benefit an organization:

1. Planning
2. Costing
3. Performance management

More specifically, labor standards are used for measuring and improving efficiency through labor definition and utilization calculations, staffing determinations, line balancing and simulations, downtime and work-flow analysis, material handling and motion pattern effectiveness, productivity measurement, worker qualification, and workplace layout redesign. Management functions such as budgeting, product and process costing, forecasting, scheduling, purchasing, and performance evaluation are enhanced with the use of labor standards. Productivity will improve throughout a facility as labor standards are developed and implemented, due to more effective and realistic planning, costing, and goal setting. By implementing engineered standards, a company will develop ways to verify its competitive position, plan for future improvements, and control potential problems before they gain momentum. For a more detailed description of the uses and benefits of standards, see Chap. 5.2.

ANDARDS

All work can be classified as short, medium, or long cycled. The predominant characteristics of each classification are followed by examples.

Short cycle operations are highly repetitive, identical, and performed continuously over extended periods of time. The individual cycle times are usually 20 seconds or less. The work is usually performed in a single workstation with a consistent layout. Little or no setup activities or walking are involved. Typical examples include food processing, check processing, mail sorting, punch press operations, subassembly, and assembly of light components and products, such as electronics, bearings, toys, or other consumer goods.

Medium cycle operations are the most common in industry, as cycle times typically vary between 20 seconds and 20 minutes. The work can be either repetitive or nonrepetitive. The work is generally confined to a specific work area, but may involve multiple workstations. Short setup activities may be encountered. Examples are plentiful in typical manufacturing, including furniture, automotive suppliers, distribution centers, retail operations, and final assembly of many different products.

Long cycle operations are nonrepetitive, nonidentical operations with cycle times ranging from 20 minutes to 1000 hours or more. The work is usually performed in multiple work areas, sometimes in different work sites, often requiring significant travel between areas. Variations in each cycle exist, and it is usual for multiple people to be involved. Regular setup activities may occur. Examples include setup of heavy equipment, nonidentical assembly, such as aircraft or shipbuilding, and other nonrepetitive activities such as machining large products, maintenance of machines and equipment, toolroom operations, material handling and transportation, and sanitation and utility work.

The major differences in setting standards for high-volume, repetitive work as compared to low-volume, long cycle work are the work measurement technique selected, the target level of accuracy, and the structure of the data. These differences lead to three major approaches to developing standards.

Direct Measurement. First, *direct measurement* can be used to set a standard for a specific operation; this is best applied in highly repetitive, identical, short cycle work. Accuracy is defined by the measurement tool used; one system to use is MiniMOST, which is designed to achieve ±5 percent deviation with 95 percent confidence over a balancing time of 500 TMUs (time measurement units), or approximately 20 seconds.

> *Balancing time* is the amount of time that must be attained before a given system or data structure's desired level of accuracy can be achieved.
>
> *Balancing effect* is the statistical phenomenon that occurs during the balancing time to achieve a system's desired level of accuracy. It is the leveling out of individual deviations (suboperations) for a smaller total deviation (standard).
>
> *Direct measurement* is defined as measuring each operation independently. The data is not used to help set other standards. This involves analyzing work using a specific work measurement tool to quantify the results, and does not result in any type of reusable data structure. This results in a very detailed, thorough labor standard, and is most applicable in short cycle, highly repetitive, identical operations.

Standard Data Worksheets. Second, *standard data* elements can be organized into a *worksheet* and used to create a standard for an operation; this applies for most manufacturing jobs, classified as medium cycle due to the variations in work from product to product or length of time between repetitive activities. A typical measurement tool is BasicMOST, and accuracy of the standards is normally set at ±5 percent with 95 percent confidence over a specified balancing time.

> *Standard data* is defined as organizing work elements into useful, well-defined building blocks. The building blocks, also known as suboperations, are created once all variations of methods have been considered and are then combined to form labor standards for various operations. The size, content, and number of these suboperations depend on the accuracy desired, the nature of the work, and the flexibility and ease of use desired. The standard data should be statistically validated to cover variations in method that may occur from station to station. The data is organized into a worksheet, which will be used to set standards.
>
> A *worksheet* is a carefully designed collection of standard data that lists all the suboperations that are likely to occur in a given area of study. Typical fields on a worksheet include category, description of data, application frequency, time, and any necessary applicator instructions. A more detailed approach to developing worksheets is presented in depth in Chap. 5.3.

Benchmark Spreadsheets. Third, *spreadsheets* with *benchmarks* can be created and used to set a standard for long cycle, nonrepetitive work by comparison. This is often done using a predetermined measurement system such as MaxiMOST, and the benchmarks are organized into spreadsheets that list the types of operations that can be performed in a defined period of time, based on the accuracy of the system. In long cycle work, an acceptable deviation for standards is typically ±10 percent with 90 percent confidence over a balancing time of 40 hours. If the nature of the long cycle operations is such that worksheets can be use to set standards, this is the preferred method.

> A *benchmark* is an engineered labor standard for a specific operation that is used to help set standards in long cycle work. The benchmark represents the amount of time to perform a known operation that is used as comparison to set a standard for an unmeasured operation.
>
> A *spreadsheet* consists of a wide variety of benchmarks slotted into time intervals with the mean value of the interval applied as the standard for that interval. This method is also referred to as the *slotting technique.*

Work Conditions. In each of the three methods for creating engineered standards, the importance must be on setting the standard based on the method of the job being studied and under defined work conditions. As conditions or methods change, such as new tooling, faster machines, or engineering modifications to products, the standards will need to be reevaluated and updated.

There are many situations in which the direct measurement approach of creating standards is both the fastest and the most economical. Assembly-line operations with short cycles and few product variations are a perfect example. There is no need to create standard data or worksheets. However, some type of standard data approach must be used in the majority of cases to ensure an accurate, cost-effective system. The standard data approach becomes more economical when there are more product variations and common tasks between products and operations. Whether using direct measurement or standard data, it is the actual measurement of the elements that establishes the normal time for the task. Allowances are then added to complete the engineered time standard. The measurement should be performed with a proven system by fully trained, qualified applicators. Common systems to use include MOST, MTM (methods time measurement), and time study. See Chap. 5.1 for a detailed description of work measurement systems.

Design and Structure of Worksheets

Worksheets containing standard data are used to help set standards, whether the task is performed manually or with the use of a computer. This is the most common method of setting standards, and leads to consistent, accurate time standards. Areas to include on worksheets: identifier of the data, such as suboperation ID, title or description, application frequency, and time. Two examples are presented in Figs. 5.4.1 and 5.4.2.

Notice in each of the example worksheets the data is divided into activity categories to help the applicator quickly find the correct suboperation. In addition to the locator number and description, the occurrence frequency and time are helpful details to include on worksheets. There are numerous ways of organizing worksheets, and using the data requires only an understanding of the methods and familiarity with the standard data contained in the worksheet. Each of these example worksheets can be used by anyone familiar with both the standard data and the methods used to perform an operation to set a standard. Since standard data is covered in Chap. 5.3, this text will assume you have a worksheet developed and are ready to set standards using that worksheet.

Consistency and Accuracy of Standards

The approach taken to developing "accurate" engineered standards is a consideration of economics and accuracy. These two factors have a direct relationship: When accuracy increases, so does the time required and the overall cost of developing standards. Conversely, as the

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	Set up		Usage per	Subop#
Job prep & completion	Clock on job		Operation	1602
	Read paperwork		Operation	2022
	Stamp paperwork		Operation	2024
Locate part (locate)	Mark part ID with wax pencil		Part	1815
Hole preparation (drill)	Set up for drill, ream & countersink	Hook & unhook air tool	Occ	1605
		Prepare drillgun	Occ	1610
	Add for composite drilling	Safety preparation (clothing)	Occ	1667
		Composite prep & clean up	Occ	1638
	Set up for countersink		Occ	1636
	Get tools ready for work		Occ	1893
	Set up for spacematic drill/countersink		Occ	1991
	Get special tools & consumables from stores		Occ	2013
Dismantle & deburr				
Trimming skin panels	Hook & unhook air tool		Occ	1605
	Prepare drillgun		Occ	1610
	Get special tools & consumables from stores		Occ	2013
	Prepare for trim panel edge		Occ	2033
	Prepare for trim & rout		Occ	2044
Reassemble & rivet	Get DNR parts (hardware)		Occ	1978
	Set up riveting tool		Occ	1793
	Hook & unhook air tool		Occ	1605
	Get tools ready for work		Occ	1893
	Get special tools & consumables from stores		Occ	2013
	Prepare for wet install		Occ	1973
Other fastener installation	Get DNR parts (hardware)		Occ	1978
	Hook & unhook air tool		Occ	1605
	Get tools ready for work		Occ	1893
	Get special tools & consumables from stores		Occ	2013
Sealing & coating	Hook & unhook air tool		Occ	1605
	Sealing—prepare & clean up		Occ	1877
	Alodine—prepare		Occ	1664
	F19—prepare		Occ	1665
	Adhesive—prepare		Occ	1990
Special operations	Get DNR parts (hardware)		Occ	1978
	Get special tools & consumables from stores		Occ	2013
	Hook & unhook air tool		Occ	1605
	Get tools ready for work		Occ	1893
Drivmatic	Set up drivmatic		Occ	1983
Inspection				
Part marking—clean assembly	Clean assembly		Order	2046
	Affix rate item tag		Order	2009
	Move large steel platform		Order	2x2027

FIGURE 5.4.1 Standard data worksheet—aircraft subassembly.

RUN		Usage per	Subop#
Locate parts, to each other, or to fixture	Small (<6″)	Part	2089
	Medium (6″–12″)	Part	2088
	Medium-large (1′–5′)	Part	2090
	Large (5′–8′)	Part	2091
	X-large (2 man)(8′–10′)	Part	2092
	X-large—hold. fixture	Part	2093
	X-large—jig	Part	2094
Drill 1 hole (#40 and #30)	Sheet metal	# holes	2078
	Composite	# holes	2078
	Titanium	# holes	2078
Countersink 1 hole		# holes	2079
Drill precision hole (close tol. fastener)		# holes	2081
Layout & drill hole		Occ	2082
Spacematic drill/countersink		# holes	2085
Install cleco (wedgelock)		# holes/3	2086
Remove parts from each other or to fixture	Small (<6″)	Part	1649
	Medium (6″–12″)	Part	1651
	Medium–large (1′–5′)	Part	1653
	Large (5′–8′)	Part	1647
	X-large—hold. fixture	Part	2012
	X-large—jig	Part	1997
Prepare for deburring		Operation	1640
Deburr hole		# holes	1641
Hand-trim between panels	X-large inst. and rem.	Part	1804–1806
	Install power clecos	# inches *3	1977
	Measure gap	Part	1652
	Mark using tape	Linear foot	1777+1623
	Hand trim	Linear inch	1654
Trim panel edge in jig		Linear inch	2053
Rout an opening		Linear inch	2045
Locate parts to each other or to fixture	Small (<6″)	Part	2071
	Medium (6″–12″)	Part	2072
	Medium–large (1′–5′)	Part	2073
	Large (5′–8′)	Part	2074
	X-large (2 man)(8′–10′)	Part	2075
	X-large—hold. fixture	Part	2076
	X-large—jig	Part	2077
Rivets	Use awl to line up holes	# rivets/6	2080
	Install solid rivet	# rivets	2083
	Cherry-max	# rivets	1866
Close tolerance fasteners	Verify length/diameter	Operation	1865
	High-lok	# rivets	2084
	Huck bolts	# rivets	2084
Wet install		# rivets	1972+2054+242
Microshave rivet		# rivets/3	1819
Get rivets from freezer (DD only)		# rivets/24	1604

FIGURE 5.4.1 Standard data worksheet—aircraft subassembly. (*Continued*)

Run		Usage per	Subop#
Nut, bolt & washer	Nut, bolt & washer	# fasteners	1845
	with cotter pin	# fasteners	1853
	with lockwire	# fasteners	1854+1776
Install anchor nut		Occ	2096
Install rivetless anchor nut		Occ	2023+2014
Torque fastener		Occ	1974+1776
Install Dzus fastener		Occ	2055
Install heli coil		Occ	1887
Install Camloc		Occ	1851
Apply sealant	Fay seal	Inch	1878
	Fillet seal	Inch	1879
	Dome seal	Fastener	1880
	Void seal	Occ	1881
Alodine	Clean & apply	Inch	2065
F19	Clean & apply	Inch	2062
Apply adhesive	Loctite	Part	2063
	Cement	Inch	2064
Install bushing/bearing		Occ	2056
Position rubber seal (gasket)		Occ	1882
Fasten rubber seal (gasket)		# holes	1888
Install laminated shim		Occ	1988
Install bonding lead		Occ	1987
Install Velcro		Inch	2001
Drivmatic	Move part to machine	Hole	1886
	Install rivets	# holes	1989
	Clean part	Sq. ft	1870
Notify inspector		Occ	1776

FIGURE 5.4.1 Standard data worksheet—aircraft subassembly. (*Continued*)

accuracy level is decreased, so are the associated costs. The most economical approach is one that allows data to be developed quickly, incorporates a simple and consistent application of the data, and reaches the desired level of accuracy. Accuracy levels vary based on several factors:

- Desired outcome or purpose of standards
- Work conditions, such as length of cycle, variations in process, repeatability
- Contract requirements

The three primary uses of standards are to plan effectively, determine costs, and manage performance. All three of these broad uses tie in to the overall purpose of managing by fact and having the necessary information available quickly and easily. Consistency in application, development, and use of the standards is vital. The desired application of the standards ties in directly with the process for developing the standards. For instance, if the goal is to schedule labor, machines, or raw materials, then the level of detail and accuracy required, and therefore

ID	Move	TMUs
1	Move part to rack or station	47
2	Place or remove part from fixture	60

ID	Install	TMUs
3	Install part using simple placement	40
4	Install part using adjustments or pressure	65
5	Install part using precision placement	90
6	Install part using black stick or pliers	150
7	Install first threaded fastener using power tool	160
8	Install additional threaded fastener using power tool	130
9	Install threaded fastener using screwdriver	280
10	Install part using tweezers	175
11	Install part using tweezers under microscope	315
82	Install tie-wrap	250

ID	Operate	TMUs
12	Push button or pull lever	40
13	Push multiple buttons up to 5 buttons	52
14	Scan first bar code using gun	120
15	Scan additional bar code using gun	80

ID	Connect	TMUs
16	Connect end LIF	70
17	Connect end ZIF	150
18	Route cable or wire (1–2) locations	70

ID	Form/cut	TMUs
19	Preform lead, wire cable, or flex using fingers	120
20	Form first lead, wire, cable, or flex using pliers	170
21	Form additional lead, wire, cable, or flex using pliers	130
22	Cut first component lead	140
23	Cut additional component lead	60
24	Cut using scissors (1–4) cuts	110
79	Cut using a knife (1–4) slices	180

ID	Apply/adhere	TMUs
25	Adhere simple or non-value-added label	90
26	Adhere and align label or overlay film	190
83	Adhere high precision label	320
27	Remove label or overlay film	60
28	Reapply overlay film	40
29	Apply first liquid adhesive using gun or syringe	140
30	Apply additional liquid adhesive using gun or syringe	100
31	Apply liquid coating using brush	160
32	Adhere strip of tape (up to 12 inches long)	150
33	Wrap strip of tape around part	220
34	Adhere strip of tape using tweezers	180
35	Tear label from printer	50

FIGURE 5.4.2 Standard data worksheet—electronic assembly.

ID	Mark	TMUs
93	Mark using check, dot, or line	110
89	Mark initials or associate ID number	120
38	Mark part using rubber stamp	85
39	Write serial number and checkmarks	310
40	Complete non-conformance tag or log entry	750
87	Test touch screen using stylus	260

ID	Align	TMUs
42	Adjust or orient component	68
43	Adjust power	220
69	Adjust laser vertically	120
70	Adjust laser horizontally	120
71	Adjust mirror	120

ID	Surface Treat	TMUs
44	Clean with air hose, swab, brush, or cloth	150
45	Remove excess material using tool	225
46	Remove debris using pick first point	90
47	Remove debris using pick additional point	50

ID	Solder	TMUs
48	Solder touch-up first point	150
49	Solder touch-up additional point	100
50	Solder seam (up to 2 inches)	270
94	Solder first point	225
95	Solder additional point	125
53	Air vac soldering	100
54	Remove solder using solder wick	210
55	Apply solder flux using squeeze bottle	70
56	Apply solder flux using marker	170

ID	Inspect	TMUs
57	Visual inspection (1–4) points	40
58	Visual inspection (5–9) points	100
60	Visual inspection (5–9) points with eye loupe or mic.	170
72	Visual inspection (1–4) points using eye loupe or mic.	110

ID	Pack	TMUs
61	Open bag and remove part	120
62	Place part in bag	210
63	Form insert around part using (5–10) folds	390
64	Form insert around part using (15–20) folds	720
65	Put on foam end caps	270
66	Form and pack box up to 12 folds	310
67	Form and pack box using 12 or more folds	480
68	Seal one end of box with packing tape	220

Time Measurement Units

1 TMU = .00001 hour
= .0006 minute
= .036 second
1 hour = 100,000 TMU
1 minute = 1,667 TMU
1 second = 27.8 TMU

FIGURE 5.4.2 Standard data worksheet—electronic assembly. (*Continued*)

the development approach, will differ from if the result is to develop standards for an incentive system where exacting requirements are necessary to ensure proper wage payment. In the first case, the industrial engineer will usually desire the standards system to achieve ±10 percent deviation with 90 percent confidence over an average workweek, such as 40 hours. In the latter case, the desired accuracy may be ±5 percent with 95 percent confidence over a balancing time of 8 hours. This results in different standard data. In both cases, it is important to be consistent when developing the standards. This allows those affected by the standards to quickly understand what is included; verify method steps, frequencies, and operator instructions; and interpret the data consistently. In another example, if the goal is to determine the labor cost for a particular product, and competition has forced the profit margin to only pennies, more detail is needed than if research and development want to know what the expected cost will be to manufacture a new product. In all of the these cases, the desired level of accuracy, the necessary level of detail, and therefore the structure of the data and even the measurement system chosen will likely differ, even though all will result in accurate, consistent time standards.

In addition to the purpose of the standards, the actual work conditions will help determine the accuracy requirements. In a highly controlled setting where methods rarely vary and cycle times are short, a high level of accuracy can be obtained in a short period of time. However, when cycles are longer and product or process variations are more likely to occur, accuracy cannot be as high or as easy to attain. In shipbuilding, the variation of any operation and the situations that arise due to weather, materials, timing, and the like will not allow for ±5 percent deviation in a standards system. A deviation of ±10 percent with 90 percent confidence is an acceptable level of accuracy with consistent development efforts. In the 1980s, the Department of Defense issued MIL-STD 1567A, which was primarily applied in the aerospace industry and states that ±10 percent deviation with 90 percent confidence is the desired level of accuracy in labor standards.

Contract requirements often specify required accuracy levels, and the standard data should be developed and organized to meet the accuracy stated. In any of the previous cases, as long as the standard data was created properly, the system accuracy will be achieved if the applicator follows the correct application rules and bases the standards on methods for defined conditions.

In addition to accuracy requirements, consistency in application of the suboperations is very important. In order to achieve proper standards, the data must be organized, easy to understand, and straightforward to apply. Consistent standards are just as important as accurate standards.

Standard practices describing how to develop standards, how to correctly use the standard data, and what work should be included in the standards are helpful tools. These practices should be defined prior to setting standards and used as a reference throughout the development effort. In addition, a standards steering committee can help ensure consistency and accuracy.

Regardless of the system chosen, the balancing time, or the purpose of the standards, the two generally accepted levels of accuracy for engineered labor standards are ±5 percent with 95 percent confidence and ±10 percent with 90 percent confidence.

Information Required Prior to Setting Standards

The approach to developing standards requires the analyst to pay attention to detail. Prior to measuring any work, the scope of an individual time standard must be determined, with products, stations, and any other parameters set. Data must be collected and studied, including but not limited to part or assembly drawings and instructions, process sheets, layouts, and tool and machine information. To develop correct standards, the analyst must also understand such facts as how the material arrives at the workplace, who is responsible for its delivery, how it is taken away, and who is responsible for removing it.

One recommendation for retrieving all necessary information is to review the work management manual as presented in Chap. 5.3. Once this information has been determined, the analyst will use one of the following techniques to create an engineered labor standard.

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Information Included in a Labor Standard

Labor standards should consist of the following information:

- Filing information
- Suboperation identifiers
- Method step descriptions
- Frequency values
- Time value for each method step
- Notation for internal method steps
- Operator instructions

Filing information includes header information to categorize and save the standard. This also ensures that each standard is unique and is not repeated or copied. Suboperation identifiers help standards applicators and users find, track, organize, and consistently apply the suboperations to create accurate standards. Method step descriptions range from generic statements to very specific language regarding the step. This allows organizations the ability to customize the standards for specific procedures and instructions, or more quickly develop generic time standards primarily used for the time values. The frequency values specify how many times or how often a method step occurs. In the case of low-frequency method steps, this number is often a small fraction; in the case of multiple operators or repetitive actions, this number is often greater than 1. The time for each method step should be included, and can be used for scheduling, line balancing, or best method determination. Internal method steps should be denoted and no time will be included in the standard for these steps. Operator instructions can be developed with standards, or input once standards have been set. Either way, the instructions will help operators understand what work to perform and when to perform it.

Developing Labor Standards

Direct Measurement. With *direct measurement,* the analyst simply documents the method and uses a work measurement tool, such as MiniMOST, to develop the normal time for the task. The method should be well documented as to content and conditions and use descriptive language. The time will be determined by the analyst by following the specific guidelines of the measurement system being used. For direct measurement, the analysis becomes the normal time by totaling the time as determined by the measurement system. Allowances are then added to develop the standard time.

Standard Data. Using the *standard data* approach to develop engineered standards is easy and straightforward. The analyst must be familiar with the standard data and its application range, and then assemble the data in the correct order according to the job being studied. This is best accomplished using a worksheet. Again, the analyst must pay particular attention to the method, and verify that the standard data descriptions are applicable for the standard being created. Tools such as MOST Data Manager or computerized spreadsheets are useful for assembling standard data into engineered time standards.

In using standard data, the analyst selects the correct elements using either a worksheet that groups the data, or by querying a database containing the suboperations. Individual categories and search criteria are employed, either manually or through the use of the computer, to obtain the correct suboperations. These suboperations are determined by method rather than time, and then are assembled in order at the appropriate frequency to arrive at the normal time for the task. There are basically two methods for using worksheets: manually filling in frequencies as methods occur (like a checklist), or listing suboperations in the order they occur at the appropriate frequency. With the widespread use of computers in work measurement, the preferred method is to list the suboperations as they occur in the correct order, and then to use a data management tool to organize the standards and summarize the labor content. In many cases, manual worksheets are still used, but more often computers and computerized worksheets are used to set labor standards. Figure 5.4.3 shows an example standard being developed from a worksheet.

Benchmarks. To create standards using *benchmarks* or spreadsheets of standard data operations, the applicator must once again be familiar with the data and the operations. The applicator selects the benchmark that resembles the operation as closely as possible based on the method that must be performed. The actual operation may, however, involve more or less work than the selected benchmark. If this is the case, the decision should be made to either use the time value for the slot of the benchmark or adjust up or down one or more slots and apply the time value for the selected slot. The predetermined times for each benchmark are assembled in order at the appropriate frequency to arrive at the normal time for the actual operation. By selecting the most representative benchmarks based on method and range of time, the applicator can quickly set time standards to meet the desired level of accuracy, which is typically ±10 percent with 90 percent confidence over a balancing time of 40 hours.

Figure 5.4.4 shows an example spreadsheet containing 15 benchmarks. In developing standards with the use of the spreadsheet, the analyst will select a benchmark and use the mean time value from the group heading (0.1, 0.2, 0.4, or 0.7 hours).

Calculations and Measures. While calculations are straightforward, several examples are included at the end of the chapter to show various methods for setting standards. In addition to typical labor standard measures, such as standard time and pieces per hour, other measures can be calculated with the data, such as hours per 100 pieces, pieces per 40 hours, and so on.

In addition to the actual methods known or observed by the applicator when setting a standard, care should be taken to include the necessary "intermittent activities" that will occur during a process at a limited frequency. Such methods as retrieving a work order, discarding a container, rearranging a line station, or changing a tool can easily be missed and must be assigned in the standard based on the average or expected frequency. Several examples of this are included at the end of the chapter.

Example Standard

Step	Title	ID	Freq.	TMUs
1		1	1	47
2		61	1	120
3	Install part using adjustments or pressure	4	1	65
4	Install first threaded fastener using power tool	7	1	160
5	Install additional threaded fastener using power tool	8	3	480
6	Adhere high precision label	83	1	320
7	Mark initials or associate ID number	89	1	120
8	Connect end ZIF	17	1	300
9	Move part to rack or station	1	1	47

Summary

Normal	1659 TMU
Allow	15%
Standard	0.01908 hrs.
Pcs/hr.	52.41

FIGURE 5.4.3 Standard developed from electronic assembly worksheet.

DEVELOPING ENGINEERED LABOR STANDARDS

SPREAD SHEET

Code: 695
Craft: Pipefitter

Task area: miscellaneous plumbing

Group A	Group B	Group C	Group D
(0.00) 0.1 (<0.15)	(0.15) 0.2 (<0.25)	(0.25) 0.4 (<0.50)	(0.50) 0.7 (<0.90)
0690-1—Faucet, washers, replace	0690-2—Sink, trap, clean	0690-24—Water cooler, connect	0690-23—Toilet bowl with flush tank, install and connect to concrete black
0690-4—Faucet, handle, replace	0690-3—Strainer, large, clean, 3″–6″	0690-25—Water cooler, disconnect cap and plug	0690-29—Wash basin, install on masonry wall
0690-19—Shower, head, replace, ladder job	0690-15—Wash basin trap, replace 1¼″–1½″	0690.78—Toilet bowl with flush tank, self-standing, mount, and connect	0690-52—Drain line, open with water or air pressure
0690-22—Flushometer, flow valve, replace		0690-46—Tee and faucet, 1″×1″×½″, cut and install in water line	
0690-35—Sink, basin, or urinal; tall piece, replace			

FIGURE 5.4.4 Spreadsheet—miscellaneous plumbing.

Engineered labor standards contain specific information regarding methods. This ensures the appropriate understanding and use of the standard, as well as providing method documentation for use by the industrial engineer, the person performing the task, or anyone familiar with the operation. Once all the method steps have been determined and defined, the analyst should pay particular attention to the possibility of internal motions or method steps. Normally, internal motions should be accounted for when using the selected measurement tool, but internal method steps, which occur simultaneously to other method steps or a process time, need to be considered at the time standard level. If a method step is determined to be internal, this is denoted with a list of the step(s) that it is internal to. The time for the method step is usually shown in parenthesis, angle brackets, or is circled, and will not affect the total time standard.

Internal Work. All work is either external or internal. When setting standards, all work should be documented, and if there are internal suboperations that occur simultaneously to other suboperations, time will not be allowed for the internal suboperations. This is most likely to happen in two circumstances:

1. Manual/machine operations
2. Multiple operator operations

Manual/machine operations occur when one operator is performing both manual work and process work. For instance, in the operation shown in Fig. 5.4.5, an operator loads three parts to a machine, starts a process, and then removes a finished part that has unloaded automatically. After inspecting and measuring the part, the operator asides it to a pallet. If the machine continues to process the part in the machine, all of the work after starting the machine would be internal and denoted as such. Since the last four steps occur while the machine is running, and the total time for the four steps (690 TMU) is less than the process time (2000 TMU), they are shown as internal to step 3 in the labor standard.

Multiple operator operations occur when the crew consists of two or more operators, who depend on each other for timing, manpower, or safety. Typically, a labor standard is set for one

Step	Subop ID	Title	Frequency	Internal to:	TMUs	Total
1	12	Load Part to Machine	3		120	360
2	34	Start Process	1		50	50
3	MO	Process Time	1		2000	2000
4	14	Remove Part from Offload Area	1	3	200	0
5	22	Inspect Part	1	3	100	0
6	7	Measure Part with Gauge	1	3	240	0
7	20	Aside Part to Pallet	1	3	150	0

Normal Time:	**2410**	TMUs
Standard Time with 15% Allowance:	**0.02772**	Hours
Pieces per Hour:	**36.08**	

FIGURE 5.4.5 Manual/machine standard showing internal labor.

operator. However, in some industries, specifically heavy assembly, large product manufacturing, and utilities, multiple operators perform tasks together and one labor standard is required, due to operator dependencies. The method for setting a standard in this case is as follows:

1. List all the work required as if there are not any dependencies. At this point, the total labor hours can be calculated by adding the suboperation times.
2. Determine the constraints, namely those items of work that cannot be done simultaneously, require several operators' attention, or involve a process time. Examples include using an overhead crane that must be attended by two operators, a long process time that cannot be shortened, and pushing a cart or product with three operators.
3. Add labor in the form of additional operators or machines as required to help meet the constraints and the desired outcome, which may be a specific task time or balancing/scheduling requirement.
4. Assign internal activities based on the constraints and number of operators available.
5. Determine the standard time for the multioperator operation.

The time it should take to perform the documented work with the number of operators included is the engineered labor standard. This is true whether one operator is used (labor-hours from step one will match the labor standard) or several operators are used to perform the work. When multiple operators perform an operation, the labor standard will be lower than the labor-hours. For a more detailed description of manual/machine operations and multiple operator operations, see Chap. 17.1.

Another special case that may be encountered when setting standards for multiple operators is loss to balance. For instance, if one operator is required full-time, and a second is needed for intermittent assistance, the best method may be to set a standard for two operators. In this case, the standard should include a special element for the lost labor utilization. See Chap. 17.8 for a detailed example.

Knowledge-Based Expert Systems. In addition to the method of setting time standards manually or with the use of a computerized system (Chap. 5.6), the use of computers can enhance creation and maintenance of standards by allowing applicators to capture expert logic into systems designed to automatically generate time standards. Using a knowledge-based expert system, such as AutoMOST, can greatly simplify the standard-setting procedure and decrease the amount of time needed. The objective is to capture the information of experts familiar with the methods and the standard data, program the expert system, and use the system to achieve high levels of standards coverage in a short period of time. The process of creating a knowledge-based expert system consists of capturing an expert's knowledge into a logical, decision-making flow. The information is programmed so a computer can find the information required and set the standard automatically, or someone familiar with the operation can answer prompted questions based on a drawing or understanding of the method or part to set the standard with the use of the expert system. See a description and examples of this in Chaps. 5.6, 5.9, and 12.5.

Validity of Standards. Once standards have been set, especially at the beginning of a standards project, and periodically thereafter, applicators should check the validity of the suboperations, benchmarks, or direct measurement analyses. In addition, the time standards should be validated by method for correct application of the data, verification of the conditions, and a check on proper frequencies. This is performed by sampling the standards at the operation level to verify that the data used is correct and the methods performed are matched with the correct suboperations. Validating by method and conditions is the only way to truly validate an engineered labor standard. Time study of an operation will uncover actual time needed for one or several iterations of the method, but may not include performance evaluation, allowances, or skill level. The methods, tools, and equipment used in the operation should match what is necessary to perform the operation, and the total standard time over the balancing time should be within the desired level of accuracy.

Qualifications of Person Setting Standards. While industrial engineers are typically needed to develop standard data, and often understand the process for developing standards, they are not necessarily the best choice for developing engineered labor standards. Familiarity with the standard data, which can be achieved by those creating the data or others once the data is finalized and validated, is the first qualification for standard setters. In addition, an understanding of the process under study and familiarity with the methods entailed are required to set engineered labor standards. Once the data is available, the applicator develops a standard based on the specific conditions being studied, which also denotes the specific method that should be followed. This can be performed by an industrial engineer, but it is often in the best interest of all involved to train those more familiar with the methods and conditions in how to develop standards. Supervisors, forepersons, and operators with a variety of shop floor experience make excellent standard setters.

Creating a position within an organization to set standards will lead to opportunities for advancement, knowledge building, and motivation for experienced operators. Using the knowledge gained by such employees results in faster standards coverage in a shorter period of time, because little time is needed to view operations, determine the best method, and so on.

In addition to using experienced operators to set standards, it is recommended that operators be trained in the approach and system used to develop standards, and how to interpret the standards. This open approach will lead to full appreciation of what the standards entail and cooperation on the behalf of those being studied who realize that the system is fair and accurate, since it is accepted and used by those familiar with the methods. This text, along with work management manuals (see Chap. 5.3), may be used as training material when instructing people in the standard-setting process.

Time Required to Set Standards. There are several ways to determine the amount of time it should take to set standards for operations. Most of the time is spent collecting information, determining conditions, and documenting the method. In addition, the applicator must pay particular attention to the correct order of the suboperations and the frequency of application. The primary factors affecting the amount of time it takes to develop standards include

- Purpose and use of standards
- Amount and level of detail of documentation available
- Applicator's knowledge of the methods used to perform operations
- Type and complexity of operations

- Process followed to develop standards
- Amount of process time included
- Length of cycle
- Amount of cycle-to-cycle variation
- Number of standards

Since every organization will have different responses to the previous factors, the time will vary dramatically from one application to another. In general, the time needed to develop engineered labor standards is a function of the complexity of the operations, the complexity of the standard data worksheets or benchmarks used, and the total standard time.

The total number of standards needed varies widely from one organization to the next. In a warehouse, 200 or 300 standards may be all that are needed to cover the work. On the other hand, a large aircraft producer is known to have over 3 million standards. In many companies, the total number of standards may be 10,000 or more.

There have been numerous measurements performed on the time required to set labor standards, but each organization will have different results. One study deals simply with the number of operators each standard setter can support. The chart in Fig. 5.4.6 may be helpful in determining the amount of time and manpower needed for manual or computerized standard setting with the use of expert systems.

Filing and Retrieval of Standards. Once the purpose, approach, and system have been identified, the system and all data should be organized to best meet the desired outcomes. The top-down technique, an excellent approach to organizing standard data, defines the structure for the data and ensures its transportability and application to applicable operations and areas. Each suboperation defined in the top-down analysis is analyzed and evaluated in relation to the method employed by the individuals performing the work. The standard data is categorized and documented as to frequency and application. This leads to a systematic and accurate approach to setting standards. This subject is fully described in Chap. 5.3.

The organization of final time standards should be approached with a long-term perspective in mind. Consider the goals of the company, the desired information, and ease of development and retrieval of the standards. With the use of computers, organizational systems and filing have become easier and therefore speed of application has increased in recent years. In addition, the ease with which applicators can retrieve time standards is increased if standards are properly organized and filed in a database. Typically, standards are created and organized by part number and/or machine and station assignments. The following are examples of filing categories for standards:

- Title
- Part number
- Operation number
- Product line
- Department

Manual or Computerized Standards Development

Type of work	Time required to set standards	Ratio of standard-setters: operators	Standards developed per labor-year
Long cycle	1–5 times standard time	1:200–1:1000	50–500
Medium cycle	4–25 times standard time	1:100–1:400	300–1000
Short cycle	4–350 times standard time (system dependent)	1:50–1:200	500–2500

Note: Use of automated systems reduces the standards development time by a factor of 2 or more.

FIGURE 5.4.6 Time required to develop standards.

- Work center
- Run/setup

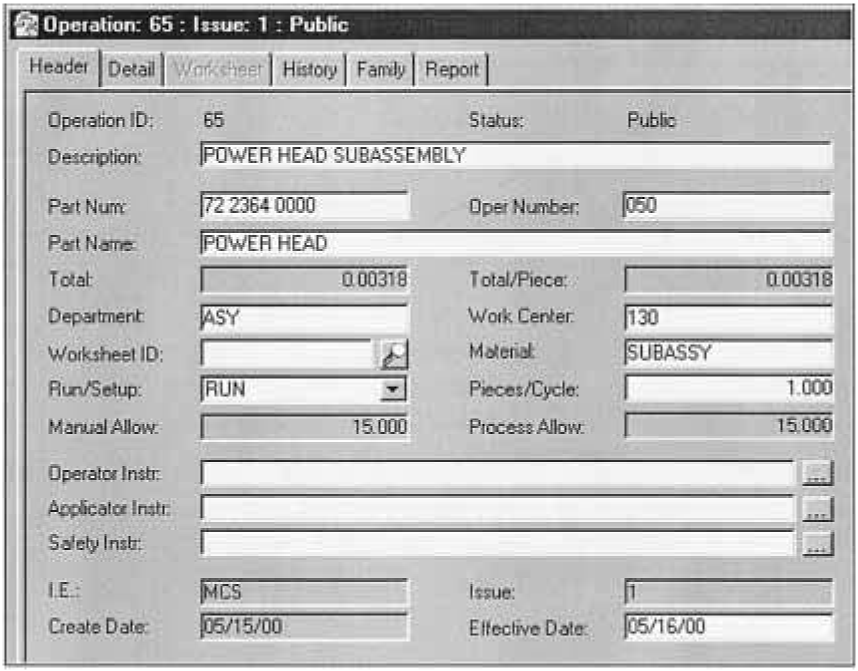
Figure 5.4.7 illustrates an example of filing information for an assembly standard.

Another way to ensure proper organization is to use a grouping of labor standards, often referred to as a *family of parts.* For example, if a standard has been created for a specific part number, and different part numbers have the same work content but different colors, all of the part numbers should be listed in the family of parts and filed with the original standard. There is no need to create a new standard for each part number. However, if the work content differs, resulting in a difference in the time standard greater than the allowed deviation, each of the part numbers will need to have a separate standard.

In addition to primary organizational information, there is often calculation data that should be included with the labor standard. Such data may include

- Crew size
- Pieces/cycle
- Allowance factors
- Manual
- Process

Crew size is used to show how many operators will be performing the operation. In general, a standard is set for one operator performing one operation. However, there are instances where multiple operators are covered in the same standard. See the previous section on multiple operator operations.



Operation ID: 65
Status: Public
Description: POWER HEAD SUBASSEMBLY
Part Num: 72 2364 0000
Oper Number: 050
Part Name: POWER HEAD
Total: 0.00318
Total/Piece: 0.00318
Department: ASY
Work Center: 130
Worksheet ID:
Material: SUBASSY
Run/Setup: RUN
Pieces/Cycle: 1.000
Manual Allow: 15.000
Process Allow: 15.000
Operator Instr:
Applicator Instr:
Safety Instr:
I.E.: MCS
Issue: 1
Create Date: 05/15/00
Effective Date: 05/16/00

FIGURE 5.4.7 Filing information for an assembly standard.

Pieces/cycle is the number of parts, products, components, and so on that will be produced at the end of one cycle of the operation. In many applications, this number is one. However, in batch type operations, the number may range into the thousands.

EXAMPLES OF ENGINEERED LABOR STANDARDS

Example of Short Cycle Operation

The measurement approach for short cycle operations is almost always direct measurement. This approach is best suited to such high-repetition, identical work. While standard data can be used in certain circumstances, direct measurement of operations is often the fastest and most economical approach. An example of this is shown in Fig. 5.4.8 and detailed here:

Situation: Information assembler and sorter—material handling.

Industry: Paper products, packaging, shipping, service.

Application: Highly repetitive, short cycle operations.

Process: Direct measurement of operation using the MiniMOST work measurement tool. Applicator simply analyzes the best method using the defined rules of the predetermined motion time system.

In this example, note the 11 method steps that the operator performs to assemble the packet with five pieces. Also observe the simultaneous motions that occur in steps 4 and 10. The reach portion of the right-hand (RH) action occurs at the same time as the reach of the left-hand (LH). As a result, the total time allowed is equal to the time required to reach with one hand. Placing one of the motions that occurs simultaneously in angle brackets designates this occurrence. Because of the high volume of output involved in this activity (in this situation, the operator averaged over 1000 packages per day), a detailed, direct measurement approach was used in this specific case. While such an approach may be employed for the assembly of informational material, any highly repetitive, short cycle activity could be analyzed by this method.

Examples of Medium Cycle Operations

The measurement approach for medium cycle operations should almost always be standard data worksheets. While direct measurement or benchmarks can be used, standard data is often the fastest and most economical approach. Examples of this approach are illustrated by Figs. 5.4.9 to 5.4.11. Figure 5.4.9 depicts the standard for a tire builder:

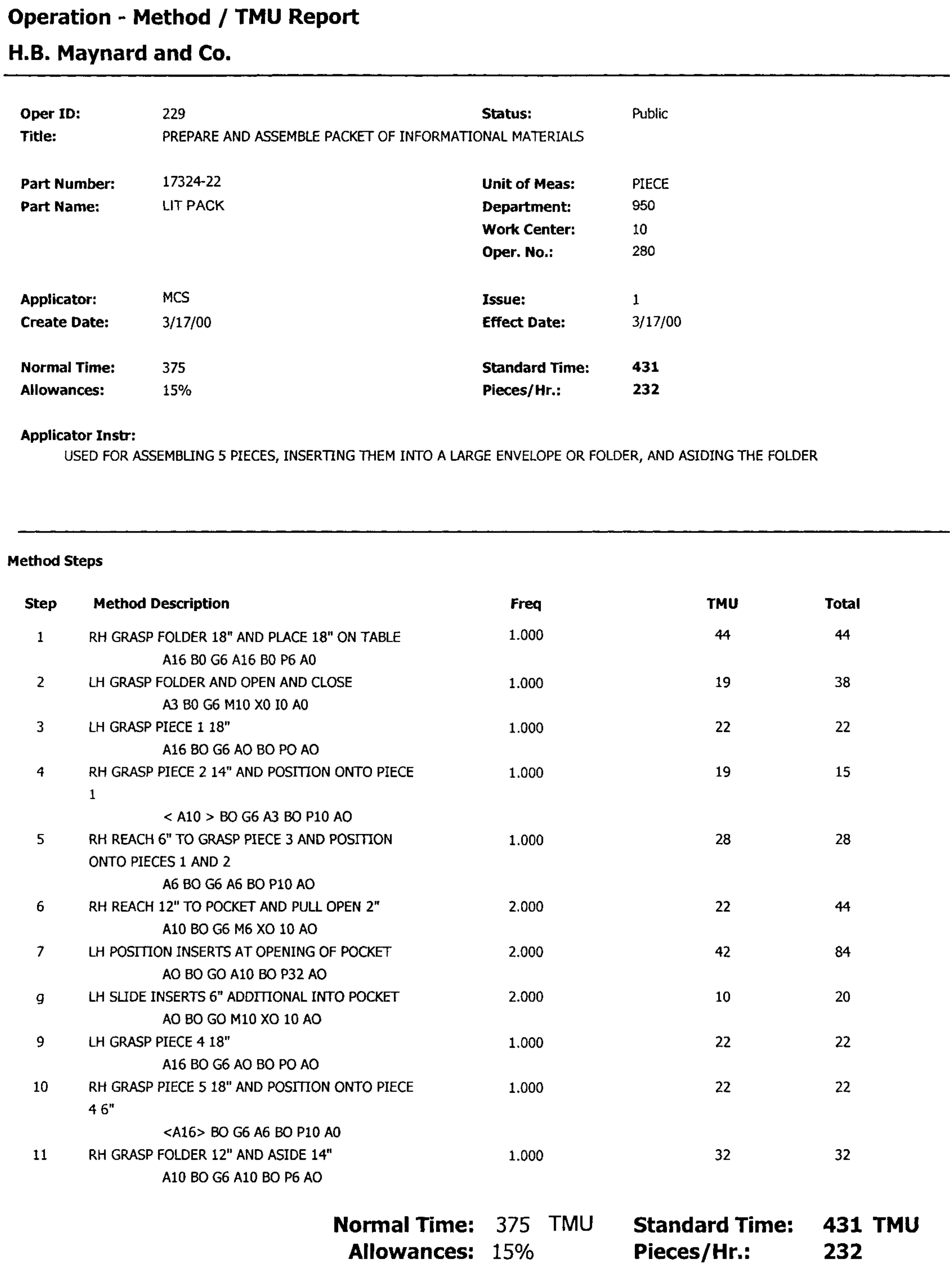
Situation: Operator is responsible for manual and machine activities to manufacture a tire.

Industry: Medium-sized manufacture and assembly. Use of machines and manual activities.

Application: Medium cycle, repetitive operations. Operator may work all day on one product or change the batch or machine tools several times. This example includes time for changing machine load as well as per-piece activities.

Process: Suboperations developed using BasicMOST. Applicator simply analyzes the best method using the defined rules of the standard data from the worksheet. This standard includes regular per-piece activities, such as cutting the raw material to length, loading to machine, stitching, and beading the parts together. In addition, intermittent activities and material change activities are included at low frequencies, based on average output per changeover. Notice also the internal activities (steps 8 and 13), which are manual methods occurring simultaneous to the machine activities (steps 7 and 12).

Figures 5.4.10 and 5.4.11 show standard data worksheet examples for warehousing:



Operation - Method / TMU Report

H.B. Maynard and Co.

Oper ID:	229	**Status:**	Public
Title:	PREPARE AND ASSEMBLE PACKET OF INFORMATIONAL MATERIALS		
Part Number:	17324-22	**Unit of Meas:**	PIECE
Part Name:	LIT PACK	**Department:**	950
		Work Center:	10
		Oper. No.:	280
Applicator:	MCS	**Issue:**	1
Create Date:	3/17/00	**Effect Date:**	3/17/00
Normal Time:	375	**Standard Time:**	**431**
Allowances:	15%	**Pieces/Hr.:**	**232**

Applicator Instr:

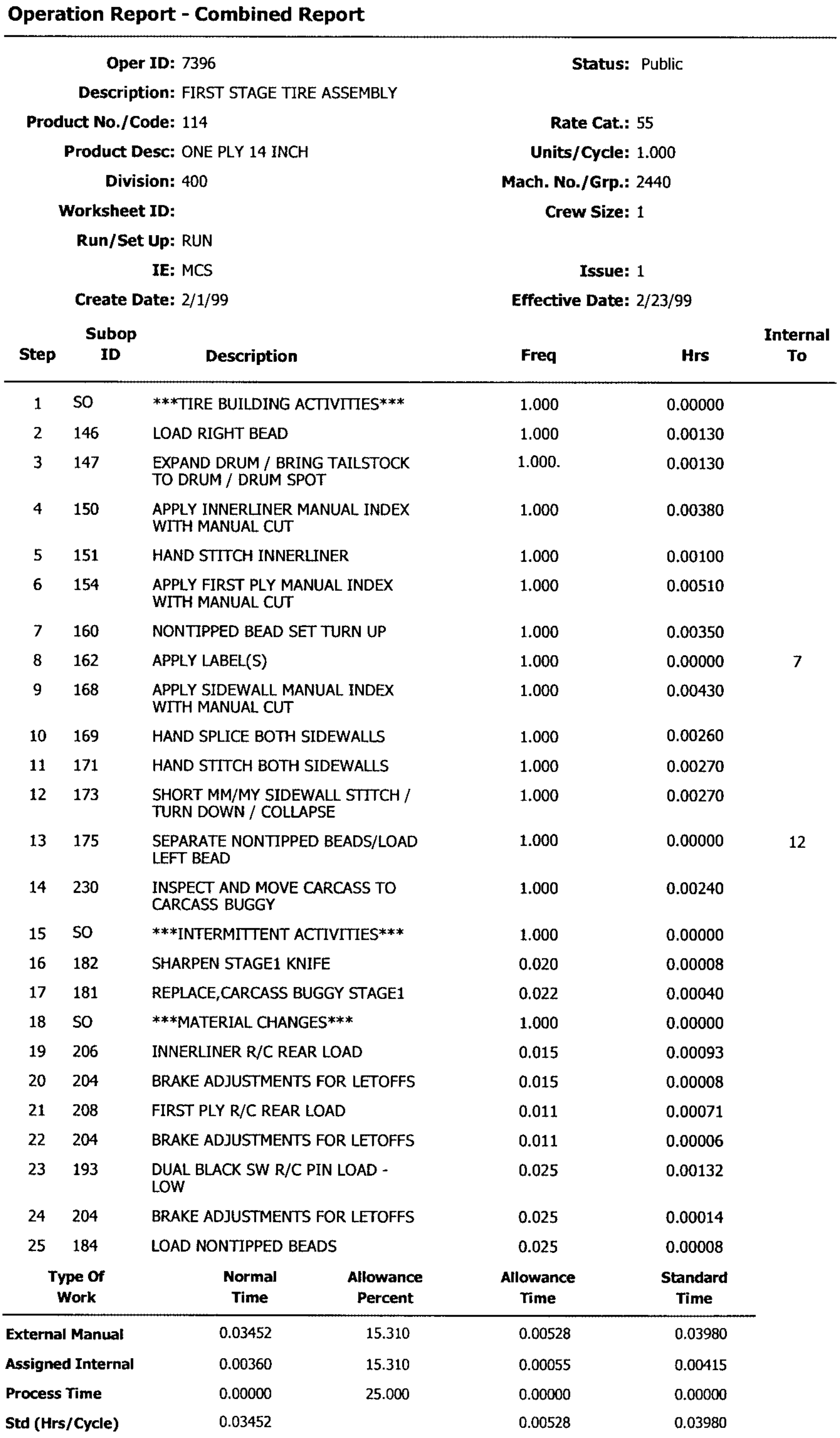
USED FOR ASSEMBLING 5 PIECES, INSERTING THEM INTO A LARGE ENVELOPE OR FOLDER, AND ASIDING THE FOLDER

Method Steps

Step	Method Description	Freq	TMU	Total
1	RH GRASP FOLDER 18" AND PLACE 18" ON TABLE A16 B0 G6 A16 B0 P6 A0	1.000	44	44
2	LH GRASP FOLDER AND OPEN AND CLOSE A3 B0 G6 M10 X0 I0 A0	1.000	19	38
3	LH GRASP PIECE 1 18" A16 BO G6 AO BO PO AO	1.000	22	22
4	RH GRASP PIECE 2 14" AND POSITION ONTO PIECE 1 < A10 > BO G6 A3 BO P10 AO	1.000	19	15
5	RH REACH 6" TO GRASP PIECE 3 AND POSITION ONTO PIECES 1 AND 2 A6 BO G6 A6 BO P10 AO	1.000	28	28
6	RH REACH 12" TO POCKET AND PULL OPEN 2" A10 BO G6 M6 XO 10 AO	2.000	22	44
7	LH POSITION INSERTS AT OPENING OF POCKET AO BO GO A10 BO P32 AO	2.000	42	84
g	LH SLIDE INSERTS 6" ADDITIONAL INTO POCKET AO BO GO M10 XO 10 AO	2.000	10	20
9	LH GRASP PIECE 4 18" A16 BO G6 AO BO PO AO	1.000	22	22
10	RH GRASP PIECE 5 18" AND POSITION ONTO PIECE 4 6" <A16> BO G6 A6 BO P10 A0	1.000	22	22
11	RH GRASP FOLDER 12" AND ASIDE 14" A10 BO G6 A10 BO P6 AO	1.000	32	32

Normal Time: 375 TMU **Standard Time:** **431 TMU**
Allowances: 15% **Pieces/Hr.:** **232**

FIGURE 5.4.8 Direct measurement standard for short cycle—assembly of information.



Operation Report - Combined Report

Oper ID: 7396 **Status:** Public
Description: FIRST STAGE TIRE ASSEMBLY
Product No./Code: 114 **Rate Cat.:** 55
Product Desc: ONE PLY 14 INCH **Units/Cycle:** 1.000
Division: 400 **Mach. No./Grp.:** 2440
Worksheet ID: **Crew Size:** 1
Run/Set Up: RUN
IE: MCS **Issue:** 1
Create Date: 2/1/99 **Effective Date:** 2/23/99

Step	Subop ID	Description	Freq	Hrs	Internal To
1	SO	***TIRE BUILDING ACTIVITIES***	1.000	0.00000	
2	146	LOAD RIGHT BEAD	1.000	0.00130	
3	147	EXPAND DRUM / BRING TAILSTOCK TO DRUM / DRUM SPOT	1.000.	0.00130	
4	150	APPLY INNERLINER MANUAL INDEX WITH MANUAL CUT	1.000	0.00380	
5	151	HAND STITCH INNERLINER	1.000	0.00100	
6	154	APPLY FIRST PLY MANUAL INDEX WITH MANUAL CUT	1.000	0.00510	
7	160	NONTIPPED BEAD SET TURN UP	1.000	0.00350	
8	162	APPLY LABEL(S)	1.000	0.00000	7
9	168	APPLY SIDEWALL MANUAL INDEX WITH MANUAL CUT	1.000	0.00430	
10	169	HAND SPLICE BOTH SIDEWALLS	1.000	0.00260	
11	171	HAND STITCH BOTH SIDEWALLS	1.000	0.00270	
12	173	SHORT MM/MY SIDEWALL STITCH / TURN DOWN / COLLAPSE	1.000	0.00270	
13	175	SEPARATE NONTIPPED BEADS/LOAD LEFT BEAD	1.000	0.00000	12
14	230	INSPECT AND MOVE CARCASS TO CARCASS BUGGY	1.000	0.00240	
15	SO	***INTERMITTENT ACTIVITIES***	1.000	0.00000	
16	182	SHARPEN STAGE1 KNIFE	0.020	0.00008	
17	181	REPLACE,CARCASS BUGGY STAGE1	0.022	0.00040	
18	SO	***MATERIAL CHANGES***	1.000	0.00000	
19	206	INNERLINER R/C REAR LOAD	0.015	0.00093	
20	204	BRAKE ADJUSTMENTS FOR LETOFFS	0.015	0.00008	
21	208	FIRST PLY R/C REAR LOAD	0.011	0.00071	
22	204	BRAKE ADJUSTMENTS FOR LETOFFS	0.011	0.00006	
23	193	DUAL BLACK SW R/C PIN LOAD - LOW	0.025	0.00132	
24	204	BRAKE ADJUSTMENTS FOR LETOFFS	0.025	0.00014	
25	184	LOAD NONTIPPED BEADS	0.025	0.00008	

Type Of Work	Normal Time	Allowance Percent	Allowance Time	Standard Time
External Manual	0.03452	15.310	0.00528	0.03980
Assigned Internal	0.00360	15.310	0.00055	0.00415
Process Time	0.00000	25.000	0.00000	0.00000
Std (Hrs/Cycle)	0.03452		0.00528	0.03980

FIGURE 5.4.9 Standard data for medium cycle standard—tire assembly.

Operation Report - Combined Report

Oper ID: 10 **Status:** Public
Description: UNLOAD ONE TRAILER
Part Number: LIVE UNLOAD **Oper Number:** 010
Part Name: TRAILER
Department: 010 **Work Center:** WH
Worksheet ID: **Material:** PALLET
Run/Set Up: RUN **Pieces/Cycle:** 1.000
Manual Allow: 15.000 **Process Allow:** 15.000
IE: MCS **Issue:** 2
Create Date: 11/4/99 **Effective Date:** 6/28/99

Step	Subop ID	Description	Freq	Hrs	Internal To
1	620	INSPECT FORKLIFT TRUCK	1/900	0.00003	
	***	1 PER 15 TRAILERS PER DAY TIMES 60 PALLETS PER TRAILER			
2	376	TRAVEL 201-300 FT. WITH REACH TRUCK	1/60	0.00014	
	***	1 PER TRAILER			
3	633	OPEN/CLOSE DOCK DOOR	2/60	0.00005	
	***	1 PER TRAILER OPEN AND CLOSE			
4	616	SET TRAILER HITCH	1/60	0.00014	
	***	1 PER TRAILER			
5	434	SET UP OR TEAR DOWN DOCK LEVELER	2/60	0.00017	
	***	2 PER TRAILER			
6	588	VISUALLY INSPECT TRAILER NUMBER	1/60	0.00005	
	***	1 PER TRAILER			
7	617	CHECK PACKING SLIP	1/60	0.00009	
	***	1 PER TRAILER			
8	373	TRAVEL 31-70 FT. WITH SIT DOWN/RC	3/4	0.00130	
	***	MOVING TWO PALLETS PER TRIP 50% AND 1 PALLET AT A TIME 50%			
9	607	CHANGE VEHICLE DIRECTION	6/3	0.00278	
	***	CHANGE DIRECTION TWO TIMES WHILE TRAVELING WITH 2 PALLETS			
10	607	CHANGE VEHICLE DIRECTION TO SEGREGATE MODELS	16/60	0.00037	
	***	2 PER MODEL, 8 MODELS PER TRAILER, 60 PALLETS PER TRAILER			
11	398	RAISE/LOWER FORKS ON REACH TRUCK 56-125 INCHES TO SORT MODELS	8/60	0.00024	
	**	1 PER MODEL, 8 MODELS PER TRAILER, 60 PALLETS PER TRAILER			
12	606	RAISE & LOWER FORKS TO LIFT FROM FLOOR	6/4	0.00015	
	***	TWO RAISING MOTIONS WITH 2 PALLETS			

FIGURE 5.4.10 Standard data for medium cycle standard—unload a trailer, page 1.

Operation Report - Combined Report

Step	Subop ID	Description	Freq	Hrs	Internal To
13	398	RAISE / LOWER FORKS ON SIT DOWN / RC 56-125 INCHES	3/4	0.00136	
	***	TWO RAISING MOTIONS WITH 2 PALLETS			
14	604	MANIPULATE PALLET TO RAISE AND LOWER	3/4	0.00209	
	***	EXTRA ADJUST PER EVERY OTHER PALLET			
15	618	CALL IN RECEIVING FOR FINISHED TRAILER	1/60	0.00041	
	***	1 PER 60 PALLET TRAILER			
16	SO	FILL IN CHECK LIST FOR INBOUND SHIPMENT	1/60	0.00278	
17	249	SCAN INHOUSE DAMAGE	1/4500	0.00000	
	***	1 OCCURRENCE PER WEEK, 15 TRAILERS PER DAY, 5 DAYS A WEEK, 60 PALLETS PER TRAILER			
18	343	KEY IN DAMAGE INFORMATION INTO SYSTEM	1/4500	0.00000	
	***	1 OCCURRENCE PER WEEK, 15 TRAILERS PER DAY, 5 DAYS A WEEK, 60 PALLETS PER TRAILER			
19	MO	CHANGE BATTERY	1/2700	0.00002	
	***	1 BATTERY CHANGE PER EVERY THIRD SHIFT, 900 PALLETS PER SHIFT 3 SHIFTS			
20	376	TRAVEL 201-300 FT. WITH REACH TRUCK TO CHANGE BATTERY	2/2700	0.00001	
	***	ROUND TRIP ONCE PER EVERY THREE SHIFTS			
21	617	CHECK PACKING SLIP	1/60	0.00009	
	***	ONCE FOR EVERY PALLET			

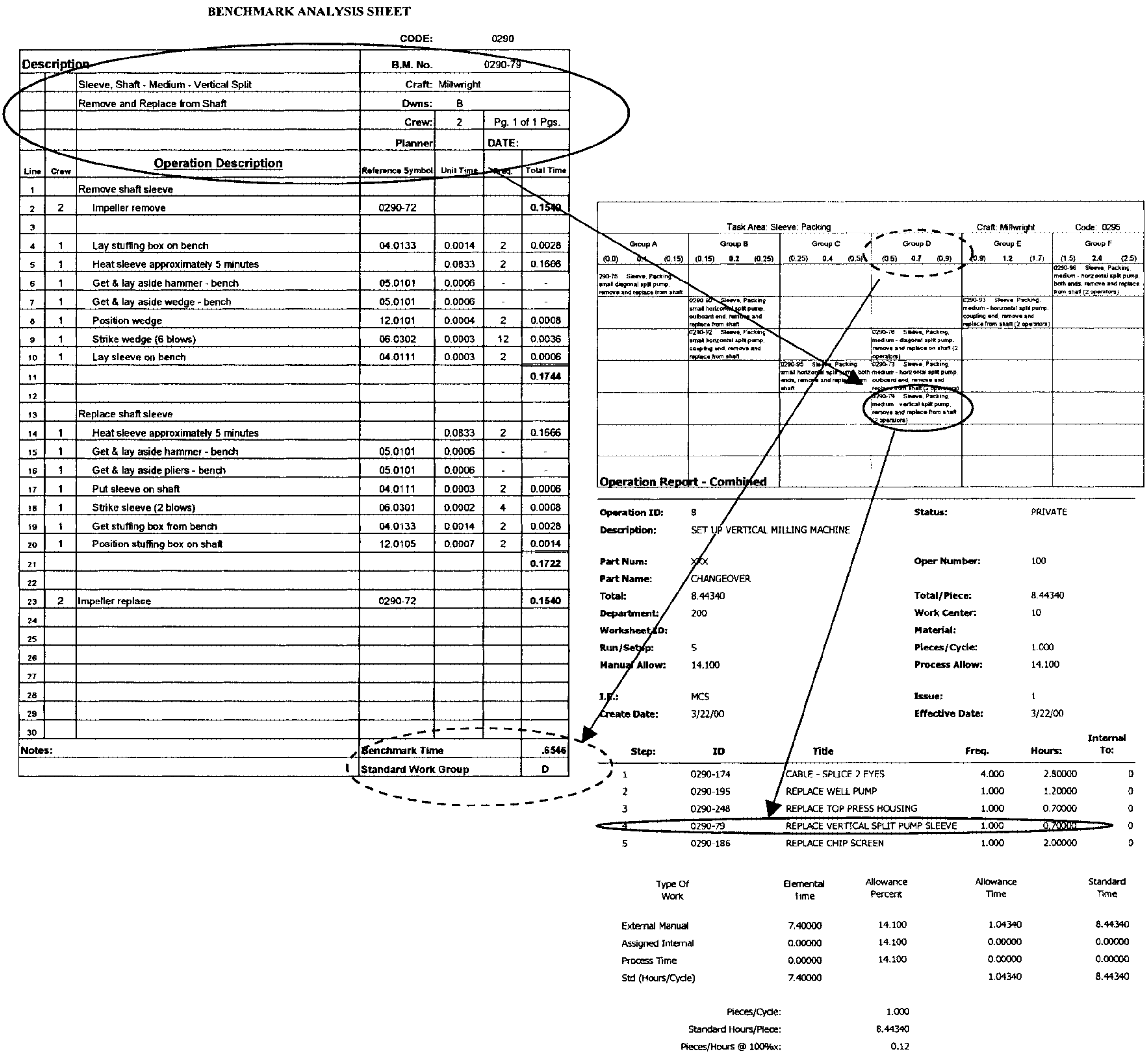
Type of Work	Elemental Time	Allowance Percent	Allowance Time	Standard Time
External Manual	0.01222	15.000	0.00183	0.01406
Assigned Internal	0.00000	15.000	0.00000	0.00000
Process Time	0.00002	15.000	0.00000	0.00002
Std (Hrs/Cycle)	0.01224		0.00184	0.01408

Pieces/Cycle: 1.000

Standard (Hrs/Piece): 0.01408

Pieces per Hr @ 100%: 71.02324

FIGURE 5.4.11 Standard data for medium cycle standard—unload a trailer, page 2.



BENCHMARK ANALYSIS SHEET

CODE: 0290

Description			**B.M. No.**	0290-79		
		Sleeve, Shaft - Medium - Vertical Split	**Craft:**	Millwright		
		Remove and Replace from Shaft	**Dwns:**	B		
			Crew:	2	Pg. 1 of 1 Pgs.	
			Planner		**DATE:**	
Line	**Crew**	**Operation Description**	**Reference Symbol**	**Unit Time**	**Freq.**	**Total Time**
1		Remove shaft sleeve				
2	2	Impeller remove	0290-72			0.1540
3						
4	1	Lay stuffing box on bench	04.0133	0.0014	2	0.0028
5	1	Heat sleeve approximately 5 minutes		0.0833	2	0.1666
6	1	Get & lay aside hammer - bench	05.0101	0.0006	-	-
7	1	Get & lay aside wedge - bench	05.0101	0.0006	-	-
8	1	Position wedge	12.0101	0.0004	2	0.0008
9	1	Strike wedge (6 blows)	06.0302	0.0003	12	0.0036
10	1	Lay sleeve on bench	04.0111	0.0003	2	0.0006
11						0.1744
12						
13		Replace shaft sleeve				
14	1	Heat sleeve approximately 5 minutes		0.0833	2	0.1666
15	1	Get & lay aside hammer - bench	05.0101	0.0006	-	-
16	1	Get & lay aside pliers - bench	05.0101	0.0006	-	-
17	1	Put sleeve on shaft	04.0111	0.0003	2	0.0006
18	1	Strike sleeve (2 blows)	06.0301	0.0002	4	0.0008
19	1	Get stuffing box from bench	04.0133	0.0014	2	0.0028
20	1	Position stuffing box on shaft	12.0105	0.0007	2	0.0014
21						0.1722
22						
23	2	Impeller replace	0290-72			0.1540
24						
25						
26						
27						
28						
29						
30						
Notes:			**Benchmark Time**			.6546
			Standard Work Group			D

Task Area: Sleeve: Packing				Craft: Millwright	Code: 0295
Group A	Group B	Group C	Group D	Group E	Group F
(0.0) 0.1 (0.15)	(0.15) 0.2 (0.25)	(0.25) 0.4 (0.5)	(0.5) 0.7 (0.9)	(0.9) 1.2 (1.7)	(1.5) 2.0 (2.5)
290-75 Sleeve, Packing, small diagonal split pump, remove and replace from shaft					0290-96 Sleeve, Packing, medium - horizontal split pump, both ends, remove and replace from shaft (2 operators)
	0290-90 Sleeve, Packing small horizontal split pump, outboard end, remove and replace from shaft			0290-93 Sleeve, Packing, medium - horizontal split pump, coupling end, remove and replace from shaft (2 operators)	
	0290-92 Sleeve, Packing small horizontal split pump, coupling end, remove and replace from shaft		0290-78 Sleeve, Packing, medium - diagonal split pump, remove and replace on shaft (2 operators)		
		0290-95 Sleeve, Packing small horizontal split pump, both ends, remove and replace from shaft	0290-73 Sleeve, Packing, medium - horizontal split pump, outboard end, remove and replace from shaft (2 operators)		
			0290-79 Sleeve, Packing, medium vertical split pump, remove and replace from shaft (2 operators)		

Operation Report - Combined

Operation ID:	8	**Status:**	PRIVATE
Description:	SET UP VERTICAL MILLING MACHINE		
Part Num:	XXX	**Oper Number:**	100
Part Name:	CHANGEOVER		
Total:	8.44340	**Total/Piece:**	8.44340
Department:	200	**Work Center:**	10
Worksheet ID:		**Material:**	
Run/Setup:	S	**Pieces/Cycle:**	1.000
Manual Allow:	14.100	**Process Allow:**	14.100
I.E.:	MCS	**Issue:**	1
Create Date:	3/22/00	**Effective Date:**	3/22/00

Step:	**ID**	**Title**	**Freq.**	**Hours:**	**Internal To:**
1	0290-174	CABLE - SPLICE 2 EYES	4.000	2.80000	0
2	0290-195	REPLACE WELL PUMP	1.000	1.20000	0
3	0290-248	REPLACE TOP PRESS HOUSING	1.000	0.70000	0
4	0290-79	REPLACE VERTICAL SPLIT PUMP SLEEVE	1.000	0.70000	0
5	0290-186	REPLACE CHIP SCREEN	1.000	2.00000	0

Type Of Work	Elemental Time	Allowance Percent	Allowance Time	Standard Time
External Manual	7.40000	14.100	1.04340	8.44340
Assigned Internal	0.00000	14.100	0.00000	0.00000
Process Time	0.00000	14.100	0.00000	0.00000
Std (Hours/Cycle)	7.40000		1.04340	8.44340

Pieces/Cycle: 1.000
Standard Hours/Piece: 8.44340
Pieces/Hours @ 100%x: 0.12

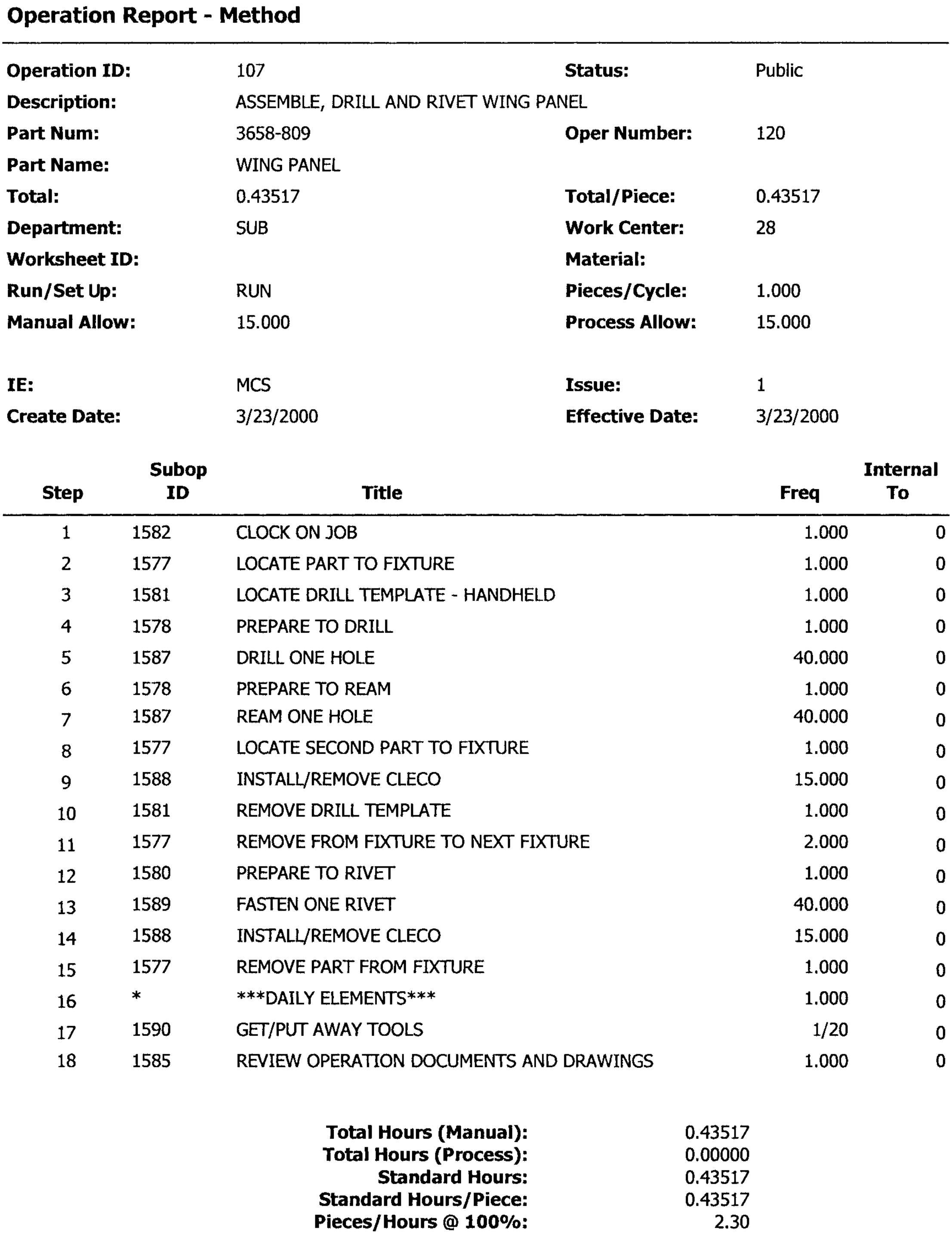
FIGURE 5.4.12 Benchmark for long cycle standard—set up milling machine.

Situation: Warehousing—operator is responsible for unloading a trailer.

Industry: Any industry that has products coming in or out by truckload on pallets. Examples include manufacturing facilities, assembly plants, and distribution centers.

Application: Medium cycle, nonrepetitive operations.

Process: Suboperations developed using BasicMOST. Applicator simply analyzes the representative method using the defined rules of the standard data from the worksheet. Each suboperation added to the standard must be verified for the correct frequency. This standard includes operator instructions documenting the frequencies, in addition to very low frequency suboperations (steps 17 to 20).



Operation Report - Method

Operation ID:	107	**Status:**	Public
Description:	ASSEMBLE, DRILL AND RIVET WING PANEL		
Part Num:	3658-809	**Oper Number:**	120
Part Name:	WING PANEL		
Total:	0.43517	**Total/Piece:**	0.43517
Department:	SUB	**Work Center:**	28
Worksheet ID:		**Material:**	
Run/Set Up:	RUN	**Pieces/Cycle:**	1.000
Manual Allow:	15.000	**Process Allow:**	15.000
IE:	MCS	**Issue:**	1
Create Date:	3/23/2000	**Effective Date:**	3/23/2000

Step	Subop ID	Title	Freq	Internal To
1	1582	CLOCK ON JOB	1.000	0
2	1577	LOCATE PART TO FIXTURE	1.000	0
3	1581	LOCATE DRILL TEMPLATE - HANDHELD	1.000	0
4	1578	PREPARE TO DRILL	1.000	0
5	1587	DRILL ONE HOLE	40.000	0
6	1578	PREPARE TO REAM	1.000	0
7	1587	REAM ONE HOLE	40.000	0
8	1577	LOCATE SECOND PART TO FIXTURE	1.000	0
9	1588	INSTALL/REMOVE CLECO	15.000	0
10	1581	REMOVE DRILL TEMPLATE	1.000	0
11	1577	REMOVE FROM FIXTURE TO NEXT FIXTURE	2.000	0
12	1580	PREPARE TO RIVET	1.000	0
13	1589	FASTEN ONE RIVET	40.000	0
14	1588	INSTALL/REMOVE CLECO	15.000	0
15	1577	REMOVE PART FROM FIXTURE	1.000	0
16	*	***DAILY ELEMENTS***	1.000	0
17	1590	GET/PUT AWAY TOOLS	1/20	0
18	1585	REVIEW OPERATION DOCUMENTS AND DRAWINGS	1.000	0

Total Hours (Manual):	0.43517
Total Hours (Process):	0.00000
Standard Hours:	0.43517
Standard Hours/Piece:	0.43517
Pieces/Hours @ 100%:	2.30

FIGURE 5.4.13 Standard data for long cycle standard—aircraft subassembly.

Examples of Long Cycle Operations

The measurement approach for long cycle operations should usually be standard data worksheets or benchmarks. These approaches are best suited to nonrepetitive, variable operations. While standard data suboperations and worksheets can be used, benchmarks are often the fastest and most economical approach. Figure 5.4.12 shows a standard for setting up a vertical milling machine and the spreadsheet listing one of the benchmarks used to set the standard:

Situation: Machine changeover.

Industry: Heavy manufacturing, large product fabrication.

Application: Nonrepetitive, long cycle operations.

Process: Benchmark approach used to measure operation using universal maintenance standard (UMS) data. Applicator simply chooses the most representative benchmark from the spreadsheet and uses the defined time for the activity.

The operation is developed by using several benchmarks that best represent the work performed. The benchmark in step 4 of the operation is also shown (0290-79).

Figure 5.4.13 is an assembly standard for the aerospace industry:

Situation: Aircraft assembly/subassembly.

Industry: Heavy assembly, large product operations.

Application: Nonrepetitive, long cycle operations.

Process: Standard data worksheet approach used to develop the operation. Applicator simply analyzes the best method using the defined rules of the standard data.

In this particular example, note the 18 suboperations that the operator performs to assemble the two parts, first by drilling holes in one part, and then riveting the second part to the first. Because of the low volume and high variability in the industry (in this situation, the operator averaged about 10 different panels per day, each with a different number of rivets), MaxiMOST suboperations were used to set the standard.

SUMMARY AND CONCLUSION

A good labor standard requires that all employees affected by the standards feel that it properly reflects the process, both in method and in time. This can best be accomplished by involving a variety of people in a standard-setting program. Industrial engineers, planners, supervisors, forepersons, and operators can together develop engineered standards by focusing on specific methods and work. Developing engineered labor standards is a straightforward task for the educated and trained industrial engineer or applicator. By using the definitions and information stated here—in addition to the appropriate use of a work measurement system and standard data to develop worksheets, benchmarks, or work measurement analyses—an organization can develop a cost-effective, accurate, and consistent standards system. The resulting standards will lead to long-term benefits as long as the system is properly installed and maintained (see Chap. 5.7).

Just like any other discipline, setting engineered labor standards is made easier by breaking the task into the defined method steps, understanding the process, and applying the data consistently. The three methods used to develop standards are

1. Direct measurement
2. Standard data worksheet calculations
3. Benchmark spreadsheet comparisons

The future of engineered labor standards is computerized data management using packaged standard data. While automated systems are becoming increasingly popular, manual standard-setting procedures will still be used far into the twenty-first century. In addition to desktop applications, computerized standards programs will be installed on palm-sized computers, and applicators and engineers will be able to quickly set standards while watching operators perform work on the shop floor.

While the future of work measurement is uncertain, primarily due to rapidly advancing technology, ongoing productivity improvements, and a shift away from labor-intensive work, engineered labor standards will still be needed in many organizations. They will be a key for managers, engineers, and shop floor employees to make quick and timely decisions, plan for the future, and manage organizations well into the future. Automated standard setting packages based on predetermined motion time systems and validated standard data will become the norm as industrial engineering moves further into the computer age.

FURTHER READING

Zandin, Kjell B., *MOST Work Measurement Systems,* 2nd ed., Marcel Dekker, New York, 1990. (book)

BIOGRAPHY

Gregory Smith is an account manager with H. B. Maynard and Company, Inc., of Pittsburgh, Pennsylvania. His experience with Maynard has consisted primarily of developing engineered labor standards domestically and internationally in a broad range of industries. In addition, he has trained hundreds of industrial engineers in this discipline. Smith holds a bachelor's degree in industrial management from Grove City College.

CHAPTER 5.5

ALLOWANCES

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This chapter describes the nature of the allowances included in time standards. It explores the need for allowances to compensate for *personal needs, relaxation* (rest) to overcome fatigue, and short unavoidable *delays* (PR&D), as well as other special circumstances. It examines the traditional thinking concerning these allowances and explores how they were developed and applied in the past. The nature of work in the twenty-first century is drastically different than it was even a few decades ago, yet allowances are often based on traditional methodology and applied as they were in the 1920s and 1930s. This chapter examines new approaches to allowances and suggests alternative methods for their determination and application, particularly in relation to allowances for personal needs and fatigue. Both are interdependent, though fatigue is almost a nonissue in the modern work environment.

WHAT ARE ALLOWANCES, AND WHY DO WE NEED THEM?

Work measurement systems (whether stopwatch, predetermined time systems, work sampling, or comparative estimating) produce task times that do not cover all of the time for which a worker is paid or for which consideration must be given for planning and scheduling purposes. They concentrate on developing basic (or normal) times for defined work content. A basic time will consist of both manual times and process times, including manual (worker-controlled) actions and machine-controlled activities—all directly related to carrying out a defined task.

Working Time Versus Nonworking Periods

During any prolonged work period (e.g., the typical eight-hour workday) people do not work continuously. They engage in activities that are not directly task-related, or they stop working entirely due to various causes. Typical nonworking periods may include such things as the following:

- Attending to personal needs (visiting a rest room)
- Resting to overcome fatigue
- Talking to other workers (about either job-related or personal matters)

- Talking to supervisors or management
- Taking recognized beverage, snack, or meal breaks
- Leaving the work area to smoke
- Waiting for quitting time or break time
- Waiting for supervisory or other workers' assistance
- Waiting for instructions, parts, materials, equipment, and so on

Many nonworking periods can be isolated and investigated to determine their cause—with a view to elimination. Other nonworking periods can be attributed to worker inefficiency. In either situation, these periods should form no part of the calculation of the time necessary to perform productive work. They should not be compensated for as part of time standards.

On the other hand, some nonworking periods are related to the work itself or occur as a direct result of being present and available for work. These include attending to personal needs, resting to overcome fatigue, and waiting during short, unavoidable delays or interruptions.

Most organizations allow their staff time for these nonworking periods by means of specified break periods or by adding extra time to basic (or normal) work times. The time needed for these nonworking aspects of the day is often calculated by adding specified percentage allowances to basic times. This results in standard times that can be used for a variety of planning and measurement purposes. Such allowances are normally referred to as *personal needs, rest,* and *delay* (PR&D) allowances or as PF&D allowances (where *F = fatigue*). Alternatively, specific time periods can be set aside during the working day to compensate for fatigue and personal needs. In some instances a combination of specified time periods and percentage additions to basic times is used.

Complex, long-cycle tasks involving more than one person (e.g., where teamwork is involved) sometimes require nonworking time allowances to permit different team members to wait for each other. Such allowances are commonly referred to as *balancing delay allowances.* Special allowances are sometimes used to cover specific situations such as machine interference.

Personal Needs. Personal needs (the *P* factor) are always present in any work environment. At one time scientific management practitioners considered that females required more time than males to attend to personal needs. With workplace equality now an established fact, this view is no longer acceptable. A common approach to personal needs is now used for both men and women. Typically, specified washroom periods (e.g., washup breaks throughout the day, at lunch, and at day's end) or a 5 percent addition to basic times are used to allow for personal needs.

Rest or Relaxation (to Overcome Fatigue). Fatigue (the *F* factor), and the consequent need for rest or relaxation (the alternative *R* factor), is the most complex work-induced element to require some form of time compensation. In the early part of the twentieth century, many work tasks involved heavy manual labor or were performed in very unsavory environments. These tasks required considerable relaxation (or recovery) time to overcome the effects of the fatigue they induced.

An *R* factor allowance of at least 5 percent has traditionally been added to normal (basic) times, but for very heavy tasks (such as those involved in foundry work or mining) fatigue allowance as high as 50 to 60 percent has been applied.

Delays of a Short, Unavoidable Nature. Throughout the workday, many interruptions to the work cycle occur. These may be due to factors inherent in the work processes, to management action (or inaction), or to factors entirely within the worker's control. Here are some examples:

- Waiting for an elevator while delivering parcels in an apartment building is inherent in the task.

- Waiting for the correct materials to arrive at a workstation is often caused by management shortcomings.
- Talking to a coworker for two or three minutes about last night's television shows is entirely under the control of the workers concerned.

Any delays directly attributable to a worker's personal decisions or preferences are not compensated in any way. Inherent delays or interruptions for which management can be held accountable are given a *delay allowance.* Such delays might consist of some or all of the following typical interruptions:

- Waiting for parts, materials, or tools
- Lining up at a store's counter
- Receiving instructions from supervisors
- Waiting for a crane or vehicle to clear a work area
- Answering coworkers' questions (work-related)
- Seeking assistance
- Looking for reference material
- Responding to an emergency alarm
- Replying to a customer query
- Waiting for more work
- Waiting for a coworker to finish a previous task

The D factor (covering short, unavoidable delays) is often taken into account by applying an arbitrary percentage addition (ranging from 1 to 5 percent) to basic task times.

Other Allowances: Special and Machine Interference. Sometimes it is necessary to include additional percentage allowances over and above those used to compensate for personal needs, fatigue, and unavoidable delays. These additional allowances might consist of some or all of the following: contingency allowances, policy allowances, machine interference allowances, and special allowances.

Contingency Allowances. These allowances are always very small and are often used to cover short periods of extra work that are largely unpredictable and not part of the measured tasks. Contingency allowances should never be more than 5 percent, and they may cover such things as correcting materials that are not to specification, additional checking or inspecting, cleaning or lubricating machinery more frequently than normal, or additional manual work caused by the malfunction of equipment. In a well-managed, well-organized work environment, contingency allowances should normally be unnecessary.

Policy Allowances. These can be used to cover any special requirement that is not easily accommodated within the time standards themselves. They are often used to modify earning opportunities within incentive programs. For example, part of an operation may be wholly machine paced, and management may wish to provide an equitable incentive payment during this time. In these circumstances, an allowance of between 15 and 33 percent may be applied to the machine-controlled time within the overall work cycle. A policy allowance may be used to cover a temporary situation for a specified period of time. For example, a learning allowance may be added to a standard for the time it takes a new employee to become fully conversant with a given task or tasks. This may take the form of a declining percentage applied over a number of days or weeks. Similarly, a training allowance may be applied to the work of someone who is expected to teach others his or her measured job.

Machine Interference Allowances. Sometimes an operator is assigned to attend to two or more machines (or other pieces of equipment) that are running simultaneously. The time standards may consist of both manual and machine-paced work elements. Sooner or later, one or more machines will be idle while the operator attends to another machine. This will produce a delay that is not normally covered by the PR&D allowance and that will cause the operator to appear to work below standard performance. To compensate for this, a machine interference allowance may be applied as a percentage addition to the standard(s). The size of this allowance will depend on such factors as the number of machines assigned to an individual operator, the extent to which the manual work elements are random, and the proportionate relationships of the manual and machine-controlled times. If these factors are known, the degree of interference can be calculated statistically and applied accordingly. Various formulas, tables, and charts are available to help, and these will be discussed later in this chapter.

HOW ALLOWANCES ARE APPLIED

Traditional practice among industrial engineers has been to determine suitable percentage additions for each factor in an empirical manner. For example, 5 percent for personal needs, 2 to 3 percent for delays of a short, unavoidable nature, and 5 to 8 percent or more for fatigue-induced rest related to light industrial work. This would typically produce a total PR&D allowance of between 12 and 15 percent. Here's a typical example of how an overall PR&D allowance of 15 percent would be applied:

Basic task time for a repetitive activity = 2.385 min

Allowances for PR&D = 15%

Standard time = 2.385 + 15% = 2.385 × 1.15 = 2.743 min

Task repetition = 175 times per 8-hr day

Daily workload = 175 × 2.743 = 480 min

Consisting of 417 min work (= 2.385 × 175)

480 – 417 = 63 min nonworking time

Thus, by adding a 15 percent allowance, the day is actually being split into 87 percent working and 13 percent nonworking time.

Any specified break period (beverage break, washup break, etc.) provides a period of relief from physical work activities. As such, breaks provide at least part of the rest or relaxation time required to overcome the effects (if any) of fatigue and attend to personal needs. Any activity involving light effort compensates for tasks requiring more effort. Therefore, attending to personal needs itself provides a degree of relaxation.

If specified break periods form part of the workday and are not included in the calculation of workload or performance, then the overall percentage allowance factor needs to be reduced accordingly. For example, say that two 10-minute beverage breaks and one 5-minute washup break are specified.

Total = 2 × 10 + 1 × 5 = 25 min for relaxation and personal needs

Work period subject to standards = 480 – 25 = 455 min per day

Estimated total PR&D required = 63 min per day (calculated as before)

Then 63 – 25 = 38 min is required via a % addition to basic times

$$\text{Required \% allowance (in addition to breaks)} = \frac{38}{455 - 38} = \frac{38}{417} = 9.1\%$$

In this example, the day of a worker who is expected to carry out 175 identical tasks with a basic task time of 2.385 minutes during the 8-hour day would be as follows:

Standard time = 2.385 + 9.1% = 2.385 × 1.091 = 2.602 min

175 tasks @ 2.602 standard min per task	= 455 min
Plus breaks, etc.	= 25 min
Total paid time	= 480 min

The preceding example illustrates how a mixture of fixed, specified break periods and the addition of percentage allowances should be accommodated. It shows that if total PR&D allowances of 15 percent are appropriate, a combination of 25 minutes of break time and a 9.1 percent addition to basic times will provide the required daily time to cover delays, personal needs, and relaxation.

The preceding examples show how allowances are applied to task times. The mechanism is always the same. What varies is how the level (either percentage or fixed time) of PR&D allowances are arrived at for individual tasks and for different types of work. The rest of this chapter will examine how this has been done in the past and how it may be done in the future.

WHAT'S WRONG WITH THE TRADITIONAL METHODOLOGY FOR DETERMINING ALLOWANCES?

Throughout the twentieth century, work changed dramatically. We have moved from an agricultural and heavy-industry society to automated manufacturing and processes and on into the information age, where most work is very undemanding in the physical sense. Yet industrial engineers still try to compensate for personal needs, fatigue, and delays in the traditional manner.

The major problem in determining PR&D allowances lies primarily with the nature of fatigue and how it can be overcome. In the past, nearly all attempts to assess the level of overall allowances have tended to treat each of the three factors as separate issues. If we look back over the use and application of allowances during the past four decades, we find the following diverse opinions.

How Personal Needs and Relaxation Have Been Treated in the Past

The first edition of *Introduction to Work Study* [1], published by the International Labour Office (ILO) in Geneva in 1964, states that rest allowances are still largely a matter of guesswork, despite the work done by physiologists and psychologists on the nature and effects of fatigue. Many scales of allowances for fatigue have been developed for various types of activity and different working conditions. Some of these appear to work satisfactorily in practice, but very often, rest allowances are the result of agreement between management and workers. For comparatively light work, allowances might be 12 percent; for heavier work, 20 percent may be a fair allowance. Established breaks allow for some relaxation to overcome fatigue, and the remainder of the required relaxation time may be taken at the workers' discretion. Factors that cause fatigue, as described by the ILO, are as follows:

- Standing
- Abnormal body position
- Use of force or muscular energy
- Poor lighting
- Atmospheric conditions
- Concentration and attention
- Noise

- Mental strain
- Monotony and tediousness

Tables of suggested fatigue allowances relate to these factors. The table quoted in the first ILO book was developed by P.A. Consultants in the early 1960s.

R. M. Currie was a British pioneer of scientific management. In *The Measurement of Work* [2], published by the British Institute of Management in London in 1965, he uses the concept of the *relaxation allowance* (RA), which is expressed as a percentage and assigns personal needs 2½ percent. Currie states that light to medium work without any abnormal circumstances requires a total RA of 12½ percent. For engineering and construction work, the RA varies from 10 to 20 percent in increments of 2½ percent. Examples include the following RA levels:

- 10 percent for walking without loads, clerical duties, light bench work
- 12½ percent for changing flanges, small valves, pump assembly/disassembly, wheeling empty barrow
- 15 percent for wheeling full barrow, changing heavy valves, removing converter heads
- 17½ percent for maintenance work in fumes (e.g., ammonia) or poor conditions
- 20 percent for lifting heavy pipes, great heat, heights over 13 m, working with a respirator

Currie maintains that a worker should be given sufficient rest to enable him or her to work at 100 percent performance on the British Standards Institution (BSI) rating scale (standard performance) without suffering more than the normal healthy fatigue to be expected at the end of the workday. Currie's book provides a table of relaxation allowances.

The British Standards Institution (BSI) scale is based on a fixed point to which it ascribes the value 100. This point represents the performance level of a qualified person who is working under highly motivated conditions (such as a monetary incentive scheme). The BSI scale does not recognize a "normal" pace since it contends that this level varies significantly from person to person and situation to situation. The BSI 100 level is equivalent to the 80 level on the original Charles Bedeaux 60/80 scale. It is roughly equal to a performance level of 120 to 125 as measured using the Lowry Maynard Stegemerten (LMS) leveling system.

Harold E. Dales, in his book *Work Measurement* [3], maintains that all work needs rest, however light that work may be. He states that the minimum rest allowance may be 6 percent and that a fair allowance for personal needs would be 4 percent for men and 6½ percent for women. These values lead to minimum relaxation allowances of 10 percent and 12½ percent, respectively, during an 8-hour day. Dales provides a table of relaxation allowance values.

In 1976, the MTM (Methods-Time Measurement) Association in the United States carried out a survey of PR&D allowance in 186 industries in both the United States and Canada. The results, published in the *Journal of Methods-Time Measurement* [4], can be summarized as follows:

% of respondents	% PR&D used
45%	15%
35%	7% to 14%
20%	16% or higher

In *Engineered Work Measurement* [5], Karger and Bayha state that personal allowances normally vary between 2 and 5 percent of the basic time. The total PF&D allowance will normally be between 10 and 15 percent (or even higher). Karger and Bayha do not provide a table of P&F allowances.

Edward J. Polk, in *Methods Analysis and Work Measurement* [6], states that either 3 minutes per hour of work or 24 minutes per 8-hour shift is a frequently used value for personal time. This level of compensation is often negotiated between management and a union. Polk

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believes that for a business to remain competitive, any personal time allowed should be reasonable. In addition, he maintains that there should be no allowance for fatigue (on top of the 24 minutes per shift for personal needs) in the standards for the great majority of jobs.

In the fourth edition of *Maynard's Industrial Engineering Handbook* [7], customary values for PF&D allowances are listed as follows:

Personal needs	3%–5%
Fatigue allowance	3%–5%
Delays	3%–5%
Total allowances	9%–15%

Maynard's maintains that firm rules or guidelines for PR&D do not exist, that only habits and traditions prevail. The handbook states that personal allowances can be readily calculated by using the duration and number of rest breaks and converting these into a percentage. The authors believe that fatigue allowances cannot be determined by observation, claiming that numerous studies have failed to arrive at any statistically sound conclusions with respect to fatigue allowances. *Maynard's* states that allowances should not be quoted separately for personal, fatigue, or delays, but rather all three should be expressed as a combined percentage.

The fourth edition of the ILO manual *Introduction to Work Study* [8] takes the same approach to PR&D allowances as did previous editions, stating that the ILO has not adopted, nor is likely to adopt, any standards relating to the determination of allowances. In relation to the PR&D aspect of work study, the fourth edition goes on to mention the work of the British Standards Institution, which summarizes some past research on the subject and proposes a methodology (*BSI DD204,* 1991). Another important consideration with respect to PR&D allowances is contained in the ILO manual, which states that in the case of a very long work cycle containing lengthy periods of unoccupied time, it may be possible for the whole of the personal needs and fatigue allowances to be taken during the unoccupied time within the cycle. It goes on to say that such periods can compensate for personal needs only if they are long enough. On the subject of fatigue, short periods of unoccupied time can be used for recovery, and any unbroken period of 1.5 minutes or longer can be reckoned as fully available for recovery from fatigue.

Benjamin W. Niebel (deceased) and Andris Freivalds, in their book *Methods, Standards and Work Design* [10], comment that a typical personal allowance for industrial workshops is 5 percent and that this appears to be adequate for the majority of males or females. This book makes use of the early personal and fatigue allowance table illustrated in the first edition of the ILO *Introduction to Work Study* [1]. An industrial survey quoted by Niebel and Freivalds shows that a sample of 42 industrial plants use PF&D allowances ranging from 10 percent (for a plant producing household electrical appliances) to 35 percent (for a steel plant).

All of the preceding discussion indicates considerable discrepancies in the approach to determining allowances and the numbers to be used. The mechanism (i.e., the calculation methodology) for compensating workers for personal needs, delays, and fatigue has remained constant for many years. However, there remains disagreement about the amounts of time required for personal needs and relaxation. Some authorities advocate one set of criteria (and associated numbers), and other authorities suggest different criteria. The practicing industrial engineer is left to make his or her own choice between competing approaches. Even the International Labour Office will not endorse one particular set of data.

Attempts to Improve Allowances Methodology

During the early 1990s, the Institute of Management Services (IMS) in Great Britain described a method for determining recovery (rest) allowances based on energy usage. This methodology contends that no recovery allowance, other than a basic 10 percent value for personal needs, is required for tasks with energy expenditure of less than 350 watts. Energy expenditure up to this level constitutes the normal energy usage to be expected in a work environment. The underlying assumption is that people are paid to work, and therefore expend energy, and that the pay itself is sufficient compensation for a certain level of fatigue. It is only beyond this level that additional time (in the form of a recovery allowance) is required. A basic allowance of 10 percent is recommended for any type of work, and this value includes time for personal needs. The IMS documentation contains details of how long people can work without taking any rest. These periods relate to levels of energy expenditure. For example, at a level of 300 watts the maximum work time before rest must be taken is 148 minutes; at 350 watts it is 72 minutes; at 400 watts it is 38 minutes.

The British Standards Institution (BSI) developed the work of the IMS and took its concepts even further by incorporating research data from many sources (e.g., Passmore and Durnin, Beale, Randle, Pandolf, Givoni and Goldman). Its primary data source is the work of Spitzer and Hettinger, published in *Tafeln für den Kalorienumsatz bei körporlicher Arbeit* (*Tables for Energy Levels of Physical Work*).

The BSI document [9] gives full details of the proposed methodology for determining allowances for personal needs and fatigue. However, the links between the levels of energy expenditure for various tasks and the corresponding percentage allowances for relaxation are somewhat tenuous. They were developed by gathering the opinions of a sampling of British industry, and thus the tables represent the levels of allowances that certain British industries have used in the past.

Even the relatively current research into fatigue allowances has still not resolved the real issue of what levels of PR&D actually *need* to be applied to different tasks.

WHAT SHOULD BE DONE IN THE FUTURE?

In this author's opinion, the only completely satisfactory way to determine relaxation allowances designed to overcome the effects of fatigue is to measure or estimate actual levels of fatigue associated with different types of work or with specific jobs.

Allowances to Cover the Effects of Fatigue

An individual's musculoskeletal and physiological response to a job depends on many factors, including his or her physical makeup and condition, the nature of the tasks included in the job, the individual's perceived and actual cognitive workload, and the environment. An analysis of these factors can be performed at two levels:

- Examination of the whole-body effect
- Examination of a localized body-part effect, specific to the system of muscles, tendons, and ligaments that make up the body part or joint

For the purpose of measuring fatigue, it is necessary to measure physiological responses to job demands. Two measures of physiological response are heart rate and hormone levels of catecholamines. A number of different heart rate response indices can be used to compare known thresholds of fatigue-inducing job demands:

- Heart rate elevation above resting
- Percent of maximum heart rate range
- Energy expenditure expressed in watts and kcal/min
- Percent maximum of predicted VO_2 (volume of oxygen)

Fatigue is a subjective concept, and whole-body fatigue can be thought of as a general sense of tiredness. Localized body-part fatigue (as well as other internal and external factors) can also affect the perception of whole-body fatigue.

How Can We Measure Fatigue Associated with Work? Heart rate is the most convenient physiological measure of job demands because of the noninvasive nature and accuracy of the testing equipment. A monitor worn across the chest transmits data to a wristwatch-like device. These data can be downloaded to a computer for subsequent analysis.

An individual's heart rate response can reflect his or her physical condition, environmental factors, physical job attributes, cognitive loading, or a combination of these factors. Heart rate increases linearly with an increase in rate of workload. To meet the demands of increased activity, muscle contractions involved in whole-body or part-body work require that the muscles convert oxygen to energy. To deliver the increased oxygen requirements to the muscles, the heart has to increase the blood flow by increasing the heart rate.

To evaluate the physiological effects of work, heart rate recordings can be made over the course of a day. They are typically carried out at 5-second intervals to ensure that variations in heart rate over short-duration tasks can be captured. A baseline heart rate response to work can be developed using a treadmill-based stress test, a bicycle ergometer, or a step test.

Heart rate measurements can be directly related to five levels of work effort:

1. Light
2. Moderate
3. Heavy
4. Very heavy
5. Extremely heavy

There are no aerobic capacity limitations for light work for at least 95 percent of the industrial population. Tasks in this category require 70 to 175 watts (1 to 2.5 kcal/min) for whole-body work. Tasks within the extremely heavy effort level are difficult for 70 percent of the industrial population to sustain for more than 15 to 20 minutes. These tasks require more than 700 watts (10 kcal/min) for whole-body work.

Light work induces no significant fatigue and therefore, requires no rest periods to overcome it. Light work can be carried out for a full 8 hours with no rest periods. At the opposite end of the scale, extremely heavy work can be sustained for only 15 to 20 minutes without a break. The fatigue involved in tasks requiring more than light effort can be overcome by resting *or by reverting to light-effort tasks.* Table 5.5.1 shows the relationships between work classification, energy expenditure, and sustainable effort. In the table, elevated heart rate (above the normal resting rate) measurements have been converted to energy expenditure in watts. A formula (discussed later in this chapter) can be applied to determine the extent of fatigue and the actual necessary rest periods.

What About Nonphysical Fatigue? Fatigue is induced by more than just physical effort. Various environmental and psychological factors can reduce a worker's ability (or will) to work at a normal pace. Such factors may require additional break time to permit recuperation from their effects. This type of fatigue is sometimes referred to as *mental fatigue* or *mental strain.* It occurs primarily due to some or all of the following factors:

- Atmospheric conditions (heat, cold, humidity, noxious fumes, etc.)
- Noise levels
- Illumination factors and levels and associated visual strain (resulting from low luminance levels, glare, flicker, contrast, color, etc.)
- Mental strain (primarily related to task complexity)

TABLE 5.5.1 Equivalent Work Effort Levels and Associated Heart Rate Response Variables, Energy Expenditure, and Work Duration Indices

Effort level	Heart rate elevation (bpm)	Percent max heart rate range (%max HRR)	Whole-body energy expenditure watts (W)	Upper-body energy expenditure watts (W)	Work duration restriction	Percent population capable
Light	0–34	0–32	70–175	up to 125	none	95%
Moderate	35–54	33–49	176–260	126–185	>2 hr	45%
Heavy	55–74	50–69	261–420	186–295	Up to 1 hr 1 to 2 hr	95% 55%
Very heavy	75–89	70–84	421–700	296–490	Up to 1 hr 1 to 2 hr	50% 25%
Extremely heavy	>90	>85	>700	>490	15 to 20 min	30%

Source: Adapted from Susan Rodgers, *Ergonomic Design for People at Work,* vol. II, Eastman Kodak Company, 1986.

- Monotony (relating to mental and vigilance tasks) and tediousness (related to the repetitious physical movements)

The majority of present-day work tasks and environments are rarely affected by these factors. Work design is currently applied in such a way that they are either eliminated or minimized. In the rare circumstances where such factors cannot be eliminated, they need to be compensated for by the addition of either specified break periods or increased percentage allowances. Some nonphysical causes of fatigue—for example, atmospheric conditions and environmental or emotional stress—result in increased heart rate. Others do not and need to be calculated by means other than elevated heart rate testing.

As an example, visual strain (and the degree to which it needs to be compensated) can be related to the degree of detectability of object(s) being examined by the eye. This parameter can be calculated using a formula developed by Blackwell. The formula uses the variables of contrast, background luminance, viewing time, and viewing angle. If the percentage detectability is 95 percent or better, no visual strain allowance is required. At less than 95 percent, an allowance of between 2 and 5 percent may be appropriate.

The calculation of appropriate levels for nonphysical fatigue is very complex, and it is largely outside the scope of this chapter. More details may be found in Niebel and Freivald's book [10].

Equating Relaxation Requirements to Measures of Fatigue. The following formula (based on research by E. A. Muller in Germany) can be used to determine the extent of required rest time in relation to work time and energy expenditure:

$$R = \frac{T(W - S)}{W - 105}$$

where R = required relaxation time in minutes
T = task time in minutes
W = energy requirement of task in watts
S = maximum daily energy level (watts) with no recovery requirement
S = 350 watts for the majority of male workers and 300 watts for female workers and older workers

The use of this equation would suggest that no relaxation periods are required for less than 350 watts of daily energy requirement. To be conservative, some authorities lower the energy threshold to 300 watts. This just falls in the **very heavy** work category and would exclude *any* physical fatigue allowance requirement for the average worker whose tasks are typically in the **light** or **moderate** categories. Note that the resting energy requirement is 105 watts (just to stay alive) within this equation. Other sources suggest resting levels of between 70 and 100 watts. The **light**-effort level is normally considered to start at 70 watts.

If We Cannot Measure Actual Fatigue, Can We Estimate Its Extent? It will not always be practical to measure the energy requirement for a given task using heart rate monitoring equipment. In such cases, consult the various tables of energy expenditure related to factors such as effort, posture, and weights moved found in *BSI 3375, Part 5*. The values can be applied on an incremental (elemental) basis to arrive at the overall energy requirement for a defined task. Table 5.1 and the preceding formula can then be used to determine required rest periods (if any).

The percentage allowance for relaxation can be calculated from the relaxation time requirements. For example, if 20 minutes of relaxation are required throughout an 8-hour day, the equivalent percentage for rest will be $20/(480 - 20) \times 100 = 4.35\%$.

Table 5.5.2 illustrates the effort levels associated with some typical tasks and jobs. More details can be found in the book by Susan Rodgers, *Ergonomic Design for People at Work* [11].

TABLE 5.5.2 Selected Examples of Effort Levels Associated with Various Tasks

Effort level	Whole-body energy (watts)	Upper-body energy (watts)	Typical tasks
Light	70–175	<125	Assembling auto trim; riding bicycle at 10 km/h; speaking in public; canning paint; nursing (excluding lifting); raking leaves; repairing shoes; inspecting or gauging; making drawings; winding armatures; machining light objects; subassembling components; sewing by hand; tailoring clothes
Moderate	176–260	126–185	Building brick wall; cleaning boiler; knocking out castings; planing softwood; general carpentry; operating press; pushing medium cart; changing car wheel; sheet-metal working; hammering and chiseling; operating lathe; polishing by hand; sorting scrap; soldering; operating crane; using screwdrivers or wrenches; delivering mail; walking on level or downstairs
Heavy	261–420	186–295	Scrubbing floors; digging trenches; pushing heavy cart; using sledgehammer; using pickax; gardening; galvanizing; laying flooring; loading vehicle; making hospital beds; plastering walls; cleaning windows; stoking furnace; stacking lumber; repairing vehicles; order picking; preparing food commercially; house painting; annealing; metal grinding; walking up 5% gradient
Very Heavy	421–700	296–490	Tree felling with ax; commercial laundry operations; shoveling sand; trench digging; sawing wood by hand; chopping wood; using jackhammer; washing carboys; hewing coal; stacking concrete blocks; stonemasonry; heavy overhead cleaning; operating printing press (load and unload); spray painting; lifting heavy boxes; climbing normal stairs or ladders
Extremely Heavy	>700	>490	Firefighting; sawing wood—double-handle saw, kneeling; removing iron or steel slag; trimming trees with ax; lifting very heavy loads for extended periods; foundry operations; opening or closing very large, stiff valves (two-handed crank or handwheel); climbing vertical ladder

It is important to note that any period of inactivity longer than 1.5 minutes provides the opportunity for overcoming fatigue via relaxation. Therefore, any time allocated for personal needs and delays will provide relaxation.

Determining the Allowance Required for Personal Needs

The time required for people to attend to their personal needs varies from person to person. Traditionally, a 5 percent allowance (as an addition to basic time) has been considered appropriate. This equates to about 21 minutes per day. Any organization that provides two 10-minute beverage breaks plus one or two 5-minute washup breaks will be allowing for personal needs at an appropriate level.

Delays: Measuring Their Extent and Allowing for Them. Work delays of more than a short, temporary nature should never be considered part of the normal workday, and they should not be included as part of standard times. They should be recorded as nonworking periods and excluded from calculations of workload or performance to standard. Long delays need to be quantified, investigated for causes, and, where possible, eliminated or reduced.

The incidence of short, nonrecurring, unavoidable delays can best be determined by carrying out random sampling studies over a representative period of time. Techniques described in Chap. 17.3 can be used for this purpose. A sampling study might show delay levels of between 0 and 5 percent of the working day. At these levels, the measured percentage can be applied as an addition to basic time.

Any incidence of delay longer than 1.5 minutes will normally provide an opportunity for relaxation. The delay time should be deducted from any time calculated as being required for rest due to fatigue.

Special or Machine Interference Allowances. These allowances fall into three categories: *contingency, policy,* and *machine interference.* They can continue to be applied as in the past. For example, the extent of contingency allowances can (and should) be determined from either activity sampling studies or full production studies. Policy allowances should be determined solely in relation to the management policies to which they relate, should be used sparingly, and should be fully documented. Interference allowances should be determined from available formulas, tables, and charts. More details can be found in Chap. 10 of Niebel and Freivald's *Methods, Standards and Work Design* [10].

Overall PR&D Allowances. This author recommends the use of specified break and washup periods as the basis for compensating for personal needs, relaxation, and delays. If two 10-minute beverage break periods plus (say) one or two 5-minute washup periods are allocated during an 8-hour day, then the resulting total of 25 or 30 minutes amounts to between 5.2 and 6.25 percent of the day. For the majority of the population, a personal-needs allowance of this size should be adequate.

Delays of a short, unavoidable nature should be determined by random sampling studies. If these reveal delays amounting to (say) 3 percent, then this is the delay percentage that should be added to normal time in the form of an allowance. A figure of 3 percent equates to about 14 minutes per day.

The total *time* allowances for personal needs and delays should be tallied. This total represents the true time required for personal needs and delays. But it also constitutes time available for relaxation from fatigue. For example, if a total of 25 minutes in breaks and 14 minutes in compensation for delays is required, then the resulting 39 minutes per day also provides the equivalent relaxation—in addition to compensating for personal needs and delays.

The amount of time required for overcoming fatigue should be determined by heart rate measurements or by reference to tables relating common work elements to energy requirements. Then the formula developed by E. A. Muller (shown earlier) should be used to determine rest period requirements. For example, if the tasks average an energy consumption level of 320 watts (within the heavy range), and the Muller formula is applied in its most conservative manner (i.e., assuming an older worker and a resting energy requirement of 70 watts), the required relaxation time will be as follows:

$$R = \text{relaxation time} = \frac{445(320 - 300)}{320 - 70} = 36 \text{ min per day}$$

Note that this 36 minutes assumes that the total of all task times amounts to 445 minutes of the day and that the energy threshold and resting levels are 300 and 70 watts, respectively.

If, in this situation, daily break periods and delays amount to 40 minutes, then no additional relaxation time is required. The 40 minutes of inactivity provide sufficient rest, and the spacing of the various nonworking periods should be sufficient to permit rest at the appropriate times. Zero percent relaxation allowance is required in this scenario. Note that the preceding formula can be used to predict relaxation times needed for work periods shorter than a full day. For example, if a task that would require 320 watts over an 8-hour day is carried out for only 1 hour, then

$$R = \text{relaxation time} = \frac{60(320 - 300)}{320 - 70} = 4.8 \text{ min}$$

This means that 4.8 minutes of rest would be required following the performance of this task for 1 hour. Other tasks, which require less or more energy, can have their rest-time requirements calculated in a similar incremental manner.

If work is of a very heavy or extremely heavy nature, then required relaxation time may be greater than the available opportunities for rest during break periods and delays. In this situation, we should first seek to reduce the energy requirements by examining and improving the work methods. For example, powered lifting devices and other tools and equipment may be added to the workstation. If it is not possible to reduce fatigue via improved methods, then a small percentage allowance for overcoming fatigue would need to be added to the basic time. Suppose that overall daily energy requirements were 400 watts, with total task times of 400 minutes. Further, suppose that, given the nature of the workers assigned to these tasks, it is appropriate to use the standard relaxation time formula with energy threshold and resting levels of 350 and 105 watts, respectively. In this situation, the relaxation time R would need to be 68 minutes. If the personal and delay times amount to 40 minutes, then an additional time of 28 minutes will need to be allowed for relaxation. This will amount to $28/(480 - 40 - 28) \times 100 = 6.8\%$. This percentage would be added to the basic time (together with the appropriate percentage for delays).

SOME WORKED EXAMPLES

The following examples assume that specified break periods are part of the workday. Any period of inactivity of longer than 1.5 minutes acts as a time of relaxation to overcome the effects of fatigue. Thus, beverage breaks, paid lunch breaks, and time for washing are all periods when the body is relatively inactive, and as such they provide time for the body to overcome any previously induced fatigue. Such break periods should always be considered as part of the personal needs and relaxation allowances. However, an unpaid lunch break can be spent doing whatever the employee wishes, which may include activities such as heavy exercise, intensive shopping, family arguments, or visiting a lawyer. Many lunchtime activities are fatiguing—sometimes more so than work! Unless management is paying for the lunch break, it cannot assume (or require) that it is being used as a period of rest, and it cannot be used to offset the results of fatigue in the same way that paid breaks can.

Example 1: A Task Involving Light Effort

In this example, we assume that the workday consists of a typical 8-hour (480 minutes) shift, with two beverage breaks of 10 minutes each and one washup break of 5 minutes prior to the midday lunch break. The work is of a medium cycle, medium effort, repetitive nature. The lunch period is unpaid. We further assume that the industrial engineering (IE) department has carried out a random sampling study that shows short, unavoidable delays running an average of 11 minutes (2.4 percent of the available working time of 455 minutes per shift) throughout the shift. The IE department has also evaluated the extent of energy expenditure and has determined that 20 minutes of relaxation time is required for the 8-hour shift. The situation is as follows:

Break and washup time $= 25$ min per shift

Measured (via sampling) delays $= 11$ min per shift

Calculated or measured relaxation time $= 20$ min per shift

The 20 minutes required for relaxation is adequately covered by the 25 minutes of break time. In addition, time spent attending to personal needs affords the opportunity to relax, as does any time spent waiting. The combined breaks and delay time of 36 minutes (25 + 11) for the shift is certainly more than sufficient to relax and attend to personal needs. It accounts for all the requirements of the P and R components of the allowances.

The 11 minutes of delay time occurs during the available working time of 455 (480 – 25) minutes. Therefore, the 11 minutes represents an addition to 444 (455 – 11) minutes of actual work time. As such, it corresponds to an allowance of 2.5 percent ($100 \times 11/444$).

If break periods are not included in workload or performance calculations, then only a 2.5 percent PR&D allowance (to cover short delays) needs to be applied to basic times to produce standard times, as follows.

Basic time for the repetitive task $= 2.385$ min

Standard time with 2.5% allowance $= 2.385 \times 1.025 = 2.445$ min

Available working time $= 480 - 25 = 455$ min

Expected performance $= \dfrac{455}{2.445} = 186$ tasks per shift

In this example the shift will be broken down as follows:

Time spent working $= 2.385 \times 186 = 444$ min

Time allowed for delays $= 2.385 \times 0.025 \times 186 = 11$ min

Specified break periods $= (2 \times 10) + 5 = 25$ min

Shift total $= 480$ min

If, however, all break periods are included in such calculations, then the level of allowances will be as follows:

Total breaks and delay time $= 25 + 11 = 36$ min per shift

Available working time $= 480 - 36 = 444$ min per shift

Required PR&D allowance $= 100 \times 36/444 = 8.1\%$

In this case,

Basic time for the repetitive task = 2.385 min

Standard time with 8.1% allowance = 2.385 × 1.081 = 2.578 min

Total paid time = 480 min

Expected performance = 480/2.578 = 186 tasks per shift

The shift will be broken down as follows:

Time spent working = 2.385 × 186 = 444 min

Time allowed for delays = 2.385 × 0.081 × 186 = 36 min

Shift total = 480 min

Example 2: A Heavy-Effort Task

In this example, we assume that the workday consists of a typical 8-hour (480 minutes) shift, with two beverage breaks of 10 minutes each and two washup breaks of 5 minutes each. The work is of a medium cycle, heavy-effort, repetitive nature. The lunch period is unpaid. We further assume that the industrial engineering (IE) department has carried out a random sampling study that shows short, unavoidable delays running an average of 14 minutes (3.1 percent of the available working time of 450 minutes per shift) throughout the shift.

The IE department has also evaluated the extent of energy expenditure and has determined that 60 minutes of relaxation time is required for the 8-hour shift. The situation is as follows:

Break and washup time = 30 min per shift

Measured (via sampling) delays = 14 min per shift

Calculated or measured relaxation time = 60 min per shift

The 60 minutes required for relaxation is not covered by the 30 minutes of break time. The combined breaks and delay time of 44 minutes (30 + 14) for the shift is not sufficient to relax and attend to personal needs. It does not account for all the requirements of the *P* and *R* components of the allowances. An additional allowance of 16 (60 – 44) minutes per shift will be required to cover all necessary relaxation and personal time. This assumes that all delays consist of waiting periods during which recovery from fatigue can take place.

The 14 minutes of delay time occurs during the available working time of 450 (480 – 30) minutes. Therefore, the 14 minutes represents an addition to 436 (450 – 14) minutes of actual work time. As such, it corresponds to an allowance of 3.2 percent (100 × 14/436).

If break periods are not included in workload or performance calculations, then overall allowance will need to be applied as follows:

Delay time = 14 min

Break time = 30 min

Additional relaxation time = 16 min

Total allowance time required = 60 min

The percentage allowance to be added to basic time to produce standard time will depend upon how workloads and/or performance are calculated. If break periods are not included in the calculations, then the allowance will be as follows:

Time available for work = 480 – 30 = 450 min

Delay time plus additional relaxation time = 14 + 16 = 30 min

Actual working time = 450 – 30 = 420 min

Percentage allowance = 30/420 = 7.14%

The calculation of a standard and expected performance will be as follows:

Basic time for the repetitive task = 2.385 min

Standard time with 7.14% allowance = 2.385 × 1.0714 = 2.555 min

Available working time = 480 – 30 = 450 min

Expected performance = 450/2.555 = 176 tasks per shift

In this example, the shift will be broken down as follows:

Time spent working = 2.385 × 176 = 420 min

Time allowed for rest and delays = 2.385 × 0.0714 × 176 = 30 min

Specified break periods = (2 × 10) + (2 × 5) = 30 min

Shift total = 480 min

If, however, all break periods are included in such calculations, then the level of allowances will be as follows:

Total breaks, rest, and delay time = 30 + 14 + 16 = 60 min per shift

Available working time = 480 – 60 = 420 min per shift

Required PR&D allowance = 100 × 60/420 = 14.3%

In this case,

Basic time for the repetitive task = 2.385 min

Standard time with 14.3% allowance = 2.385 × 1.143 = 2.726 min

Total paid time = 480 min

Expected performance = 480/2.726 = 176 tasks per shift

The shift will be broken down as follows:

Time spent working = 2.385 × 176 = 420 min

Time allowed for delays = 2.385 × 0.143 × 176 = 60 min

Shift total = 480 min

Example 3: A Tedious Task Involving High Visual Strain

In this example, we assume that the workday consists of a typical 8-hour (480 minutes) shift, with two beverage breaks of 10 minutes each and two washup breaks of 5 minutes each. The lunch period is a paid break of 30 minutes. The work is an inspection task, which is a very tedious, very monotonous task that involves high visual strain. We further assume that the industrial engineering (IE) department has carried out a random sampling study that shows short, unavoidable delays running an average of 12 minutes (2.9 percent of the available working time of 420 minutes per shift) throughout the shift.

The IE department has also evaluated the extent of energy expenditure and nonphysical fatigue and has determined that a total of 65 minutes of relaxation time is required for the 8-hour shift. The situation is as follows:

Break, lunch, and washup time = 60 min per shift

Measured (via sampling) delays = 12 min per shift

Calculated or measured relaxation time = 65 min per shift

The 65 minutes required for relaxation is not covered by the 60 minutes of breaks and lunchtimes. The combined breaks and delay time of 72 minutes (60 + 12) for the shift *is* sufficient to relax and attend to personal needs. It accounts for all the requirements of the *P* and *R* components of the allowances.

The 12 minutes of delay time occurs during the available working time of 420 (480 – 60) minutes. Therefore, the 12 minutes represents an addition to 408 (420 – 12) minutes of actual work time. As such, it corresponds to an allowance of 2.9 percent (100 × 12/408).

If break periods are not included in workload or performance calculations, then only a 2.9 percent PR&D allowance (to cover short delays) needs to be applied to basic times to produce standard times, as follows:

Basic time for the repetitive task = 0.575 min

Standard time with 2.9% allowance = 0.575 × 1.029 = 0.592 min

Available working time = 480 – 60 = 420 min

Expected performance = 420/0.592 = 710 tasks per shift

In this example, the shift will be broken down as follows:

Time spent working = 0.575 × 709 = 408 min

Time allowed for delays = 0.575 × 0.029 × 709 = 12 min

Specified break periods = (2 × 10) + (2 × 5) + 30 = 60 min

Shift total = 480 min

If, however, all break periods are included in such calculations, then the level of allowances will be as follows:

Total lunch, breaks, rest, and delay time = 60 + 12 = 72 min per shift

Available working time = 480 – 72 = 408 min per shift

Required PR&D allowance = 100 × 72/408 = 17.6%

In this case,

Basic time for the repetitive task = 0.575 min

Standard time with 17.6% allowance = $0.575 \times 1.176 = 0.676$ min

Total paid time = 480 min

Expected performance = 480/0.676 = 710 tasks per shift

The shift will be broken down as follows:

Time spent working = 0.575×710 = 408 min

Time allowed for delays = $0.575 \times 0.176 \times 710 = 72$ min

Shift total = 480 min

The foregoing examples illustrate the fact that for light tasks, no fatigue occurs and no relaxation allowances are required. For the majority of moderate tasks, normal break periods will be sufficient to provide adequate rest. Only tasks in the heavy or higher categories will require any relaxation *R* allowance over and above that provided (in the form of recovery time) during break, paid lunch, and delay periods.

CONCLUSION

In the opinion of this author, most work in the twenty-first century will be light or moderate in terms of energy requirements. As such, either no fatigue will occur or the low levels encountered will be adequately covered by normal break periods.

In addition to established beverage and washup breaks, which will cover personal needs (the *P* factor), only small allowance percentages (perhaps in the range of 1 to 5 percent) will need to be applied to cover short, unavoidable delays (the *D* factor). The appropriate percentages should be established using sampling techniques.

Only work requiring energy expenditure in the heavy or above categories will need additional allowances to cover relaxation (the *R* factor). The level of relaxation allowances should be established by either measurement of fatigue or by consulting appropriate work/energy tables.

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BIOGRAPHY

L. John Allerton, CMC, is a management consultant based in Ottawa, Ontario, Canada. His consulting career started in 1964 when he was employed by H.B. Maynard and Company in the United Kingdom. He emigrated to Canada in 1977 and joined Stevenson & Kellogg (now part of KPMG). With both these companies Mr. Allerton was involved in all aspects of industrial engineering, specializing in work measurement, methods engineering, and maintenance management. In 1992 he and two partners formed LINX Participative Consultants, which specialized in providing consulting services to the postal industry (primarily Canada Post Corporation and the U.S. Postal Service). LINX was subsequently acquired by EDS and eventually became part of A.T. Kearney.

Mr. Allerton was a pioneer of MTM in the United Kingdom and assisted in the development of the Maynard Operation Sequence Technique (MOST). He holds a B.Eng. degree from the University of Liverpool and is a Certified Management Consultant (CMC).

Source: MAYNARD'S INDUSTRIAL ENGINEERING HANDBOOK

CHAPTER 5.6

COMPUTERIZED LABOR STANDARDS

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Computers have revolutionized the world. Computers have changed the way businesses are run, the way they function day to day, and how people perform their daily tasks. The process of work measurement and developing engineered labor standards has also undergone dramatic change due to the introduction of computers. Industrial engineering is not the same as it was 10, 20, or 50 years ago. Computers are an integral part of the day-to-day tasks in engineering.

This chapter explores the background of computers in labor standards systems, and compares manual and computerized methods of developing standards. By explaining the attributes of available systems and introducing systems on the market today, this text examines the subject as it currently exists and concludes by painting a picture of tomorrow's computerized labor standards systems.

BACKGROUND OF COMPUTERS IN LABOR STANDARDS SYSTEMS

Computer technology has been the driving force of productivity improvement over the past four decades. Systems that used to encompass entire rooms and were used by few, now rest in the palm of a hand and are used by virtually everyone—including industrial engineers. The access to technology has significantly increased industrial engineers' productivity. Applications such as simulation, regression analysis, and work measurement are performed in a fraction of the time they used to take. This time-saver allows industrial engineers to focus on additional value-added tasks, which also increase productivity and profitability.

Historically, work measurement was performed manually with pencil, paper, and stopwatch. Industrial engineers would go to the production floor, observe operations, document method steps, and measure time. Then from their office, the elements would be summarized to form the raw time. Allowance factors and auxiliary instructions were applied, and finally the standard would be published. This was a laborious, yet necessary task.

As industrial engineering became better known and respected throughout industry, the industrial engineer's workload increased significantly. Industrial engineers became responsible for scheduling, cost justification, safety, ergonomics, and simulation, among other tasks. This posed an interesting challenge, namely, how to complete the additional tasks while still fulfilling the more traditional responsibilities such as work measurement. The use of computer tools would prove to be the answer.

In the mid-1960s, some of the first computer applications in the industrial engineering field surfaced. These tools were used for a variety of applications including work measurement. During this time, Management Science Incorporated introduced Univel, one of the first commercially available computerized work measurement packages. This tool allowed industrial engineers to develop engineered work standards and manage data using mainframe computers.

During the 1980s, traditional engineering departments began to decrease in size as many engineers were absorbed into other functional departments. This presented an interesting challenge to companies who were decreasing the size of engineering departments, but had more engineering work to perform. Enter the era of personal computing and the use of technology to assist engineers in their daily tasks. During the 1970s and 1980s, several companies developed computerized applications to assist industry in meeting the increased workloads. The major systems available were CAPES, Maynard Computer Systems, MTM/4M, and Univel. The majority of these systems were character-based systems running in MS-DOS.

In the 1990s, Microsoft's Windows operating system became the standard platform for most software applications, including work measurement systems. As the decade came to a close, most computerized work measurement systems were using client/server technology. This advancement increased the access to such engineering tools and also greatly improved application performance.

This natural evolution of computing has allowed today's smaller industrial engineering departments to accomplish the same amount of work, if not more, than the large departments of the 1960s and 1970s. Modern day industrial engineers can only afford to spend a fraction of their time performing work measurement. This is possible due to the use of computerized tools, such as computerized labor standards systems. These tools allow industrial engineers to add more value to the organization and save the company time, money, and resources.

COMPUTERIZED LABOR STANDARDS SYSTEMS

Comparison of Manual and Computerized Labor Standards Systems

There is little difference between a standard developed manually and a standard developed using a computer. Both represent the time to perform a specific task under specific working conditions. Both manual and computerized standards can be used to verify a method, plan a schedule, determine costs, and even measure performance. Although the result may be the same, there are major differences in the process of achieving these results.

There are many benefits to using computers to measure work as opposed to performing the task manually. Foremost is the ability to create and store all information electronically in a central location, typically a database. This database can be shared among users and accessed throughout a facility or over a wide area network. Shared data promotes more accurate, consistent, and efficient development of standards, and simplifies data maintenance.

Manual procedures for developing standards oftentimes lead to inefficient data development because engineers tend not to share the data between departments or facilities. This results in the same or similar work being measured many times over—sometimes with different results. This in turn adversely affects the credibility of all the standards.

When comparing manual and computerized methods for standards development, several factors should be considered, specifically:

- Speed of application
- Ease of standards development
- Consistency and accuracy of standards
- Standards maintenance

Speed of Application. A primary benefit to investing in a computerized labor standards system is the increased engineering efficiency gained by the speed of application. Computerized systems are most effective when used in conjunction with a standard data approach. This combination speeds the development of standards by enabling engineers to reuse data elements rather than remeasuring work. (See Chap. 5.3 for more information on standard data concepts.) Standard data concepts can be used when developing standards manually, but the benefits realized are not nearly as great due to the limitations of a physical filing system, as opposed to an electronic one. Field studies indicate that computerized applications are three to five times faster than manual applications, depending on the number of standards being developed.

Using manual methods and filing systems to create, store, and maintain standards can be effective if the total number of standards is small. If the purpose is to create 10 or 20 standards, a manual system is probably the most viable option. However, if the total number of standards required is much larger or method and process changes are expected, a computerized system will be more efficient, both in the up-front development and long-term maintenance of the standards.

Ease of Standards Development. Computerized standards systems allow engineers to develop standards in a fraction of the time it would take them manually. "Drag and drop" functionality and advanced database queries allow engineers to find and/or add data elements much faster than manual systems. User-friendly icons, online help, and useful functions such as custom report options, consistent filing information, and automatic calculations make using a computer faster and easier than manual standard-setting procedures.

Manual methods for standards development are very clerical in nature and do not provide a good mechanism for standards tracking and maintenance. Computerized systems eliminate the clerical aspects by automatically calculating time values, adding allowances, tracking standards history and performing mass updates.

Consistency and Accuracy of Standards. The use of computers greatly improves the consistency and accuracy of work measurement and standards development. Computer data entry, automatic calculation of standards, menu-driven drop-down lists, and application rules contained within a system all help applicators develop standards consistently and accurately. These functions eliminate wasted time spent reworking standards, re-creating lost standards, and searching for data.

When using manual systems, engineers are more likely to make simple arithmetic mistakes and also have a much greater chance of misapplying a work measurement rule. It is very difficult to eliminate these types of errors in a manual system.

Standards Maintenance. One database containing all necessary information is much easier to maintain than paper-based filing systems. The amount of time wasted physically searching, filing, and retrieving will often justify the implementation of a computerized system. Applicators can quickly search the database, determine if a standard exists, and have the ability to use, update, replace, or delete the standard. By correctly identifying and using or revising the existing standard rather than creating a new standard, the applicator saves time, and the system remains easy to maintain and use. The result is a smaller and more manageable set of unique standard data and standards.

Attributes of Computerized Standards Systems

A good computerized standards system should consist of

- Flexible filing methodology
- Easy input of method data
- Automatic calculations
- Online help and training
- Quick storage and retrieval of data
- Mass update capabilities
- Simulation of updates
- Data transfer functionality
- Report customization
- Security settings

Flexible Filing Methodology. The filing methodology should be flexible and allow an organization to properly create and store data in an efficient, logical order. The number and type of fields used to store this information should be customizable, yet fixed once a system is running to ensure consistency and continuity. Example filing information for standards might include

- Description of standard or operation
- Part number
- Part name
- Location (workcenter, department, etc.)
- Identifier of the standard

Easy Input of Method Data. Data can quickly and easily be input into computerized systems by using drop-down menus, point and click applications, computerized pick-lists, and drag and drop functionality. Engineered standards can be developed with little software training because most systems are mouse and keyboard friendly, and even contain rules on when and how to use data appropriately.

Systems are available that have predeveloped work measurement elements, which can increase the speed of work measurement by three to four times that of a system without predeveloped elements. In addition, these elements will have generic method descriptions attached, which further speeds up the data development process and simplifies the data input process.

Automatic Calculations. Any calculations should be performed automatically and be programmed or defined by the user as desired. While there are standard calculations included with most computerized systems, the flexibility to add, delete, or alter the formulas is a more useful attribute than standardized formulas. Automatic calculations generally include

- Normal time
- Manual time
- Process time
- Allowance time
- Standard time
- Pieces or cycles per hour

Online Help and Training. The system should be easy to use for computer literate applicators, and provide help as needed. Training should be available from the system provider, both in online help within the software, and in the form of a tutorial or instructor-led guidance.

Storage and Retrieval. By storing information in a computerized system, applicators have the ability to develop an organizational system to efficiently label data and quickly retrieve it when needed. Allowing users access to the data from personal computers greatly increases the speed of creation, storage, and retrieval of the information. The shared database, especially in a client/server application, allows many users to access and use the standards as they are needed from any computer linked to the database (local area network or wide area network).

With the advent of web-based technology, computerized systems now allow users to e-mail data from one system to another. This is particularly powerful for companies that have multiple facilities that perform similar tasks but maintain different databases.

Mass Update Capabilities. In addition to storage and retrieval in a central database, computerized labor standard systems should allow the applicator to perform mass updates. This means that the entire database, or a portion, can quickly and easily be changed automatically rather than manually. For instance, if a new conveyor system is installed, and each operator on an assembly line must push a button after completing a cycle, and time for this activity needs to be included in each standard, the question is how much time should it take to update the standards? Manually, this may take several days, depending on the number of standards. Using a computer, this would take a matter of minutes or hours, depending again on the number of standards and the size of the database. Likewise, if the conditions change, such as methods, layout, or tooling, the standards will most likely change. Using a computer's ability to quickly change an entire database, or selected items within a database, will improve the applicator's consistency and speed in maintaining standards.

Simulation of Updates. The ability to simulate changes before updating the standards database can be a powerful timesaving feature. Rather than making the changes directly, a simulation can be run prior to the update to ensure that proper changes will be made. Simulations can also help optimize line balances and facility layouts, product and labor costs, and illustrate the results of improvement proposals or conditional changes. For example, if a proposed engineering change is made on a product, and four pushpins are to be used for assembly rather than two pins and two screws, what is the time that is saved? A simulation of this change could be performed in a matter of minutes, and the information could then be used to make a more informed decision prior to implementation.

Transfer of Data. While a database contains all the necessary information for the standards system, there should be a method of transferring the data to other systems, such as manufacturing resource planning (MRP), enterprise resource planning (ERP), or simulation systems. One way is to use one database for all applications. Another way is to use a transfer function that outputs the data into a widely recognizable type, such as ASCII code. The benefits of this functionality are numerous, but revolve around usability of the data in scheduling, planning, and costing systems. This benefit of using a computer to organize, create, and maintain labor standards and the ability to quickly transfer the information to another computer program, applicator, or even a different facility is vital. The transportability of the data, all stored in a central database, ensures accuracy, consistency, and efficiency in creating, storing, retrieving, using, and updating standards.

Report Customization. While the data resides in a common, shared database, and can be transferred out or linked to other systems, report writing functionality is a necessary feature. Many systems contain various reporting formats and the ability to preview and print desired reports. In addition, data should be accessible for customized reports, either in the software or through the use of another program. Typical reports include a combination of any or all of the following:

- Filing information
- Method steps
- Time values
- Internal method steps
- Manual and process times
- List of standards by product, part number, etc.
- Operator instructions

Security Settings. Computerized labor standards systems should contain security-setting features. Only those trained in the use of the work measurement tool and the software system should have access to changing the database. User identification codes and passwords are typically assigned by a system administrator to ensure system integrity. In addition, high-level standards systems often include levels of privileges, such as create, read-only, administrative, and update.

COMMERCIALLY AVAILABLE COMPUTERIZED STANDARDS SYSTEMS

A variety of computerized labor standards systems are available on the market. While the systems all perform the same basic task, that is, to develop engineered labor standards, each system does this in a unique manner using different measurement systems.

When determining which system is the best for an organization, one should consider the following criteria:

1. What are the specific needs of the organization? In other words, what will the company be using the system for? Performance management? Incentive payment calculations? Scheduling? Costing? This is a critical step in determining what system is best for your organization, since it will provide insight as to what features will be needed to accomplish the desired tasks.
2. What is the cost versus benefit of implementing the system?
3. What software support mechanism does the system provider offer?

The following is a brief summary of the more commonly used computerized labor standards systems available at the time of publishing. The list is not intended to promote one system over another, but to provide the reader with a base knowledge of what is available.

Product: MOST® for Windows™, MOST® Data Manager

Company: H. B. Maynard and Company, Inc.

Measurement systems: BasicMOST®, MiniMOST®, MaxiMOST®

MOST® for Windows™ is a computerized work measurement tool that enables users to develop and maintain standard data work elements using MOST work measurement systems. The data elements are developed and filed in a database using customizable, user-defined header categories.

The system features the ability to select, drag, and drop common work methods from a library of commonly used sequence models, which comes as a standard feature of the software and can be added to by the user. Analysts can also develop new, or edit existing, work elements. This functionality allows users the ability to directly enter data or use drop-down lists, which contain the rules of a MOST application. Online help, error-proofed method step data entry, and customizable filing information are also standard functionality.

MOST® Data Manager is a computerized data management tool that enables users to develop time standards and process plans based on the standard data work elements developed in MOST for Windows. The data developed using this package is also filed in customizable, user-defined header categories.

The primary manner for developing time standards using MOST Data Manager is through the use of an electronic worksheet. The system comes with a variety of standard data work elements and worksheets that allow analysts to measure work almost immediately. Analysts can also develop their own custom worksheets.

The system also has additional features such as customizable calculations and reporting, online help, data transfer, mass update capabilities, history tracking, and auxiliary data storage.

Figure 5.6.1 shows an example standard developed with MOST Data Manager.

Product: MTM-LINK

Company: MTM Association

Measurement Systems: MTM-1™, 4M®, MTM-UAS™, MTM-UAS Standard Data, MTM-MEK™, MTM-MEK Standard Data, MTM-C™, MTM-V™, MTM-TE™, MTM-M™, and MTM-HC™.

MTM-LINK® is designed to create and maintain a standards database. Applying data from any source, it can function as a stand-alone system or be fully integrated into other business systems.

MTM-LINK is an element-driven system supporting three levels of data. All data is stored in a database where each element is defined by an element code, description, and time value. Assigning elements to an operation results in the development of an operation level standard. This task can be accomplished in a variety of ways including direct assignment of elements or the use of various artificial intelligence techniques to automate the process of assigning elements to operations. Combining operations results in the development of a routing.

MTM-LINK also incorporates mass update capabilities, the export and import of data, support for graphics and video, support for PDF files, methods improvement indices, mathematical formulas, internal calculations, and maintenance of complete operation-level histories.

An example time standard created with MTM-LINK is shown in Fig. 5.6.2.

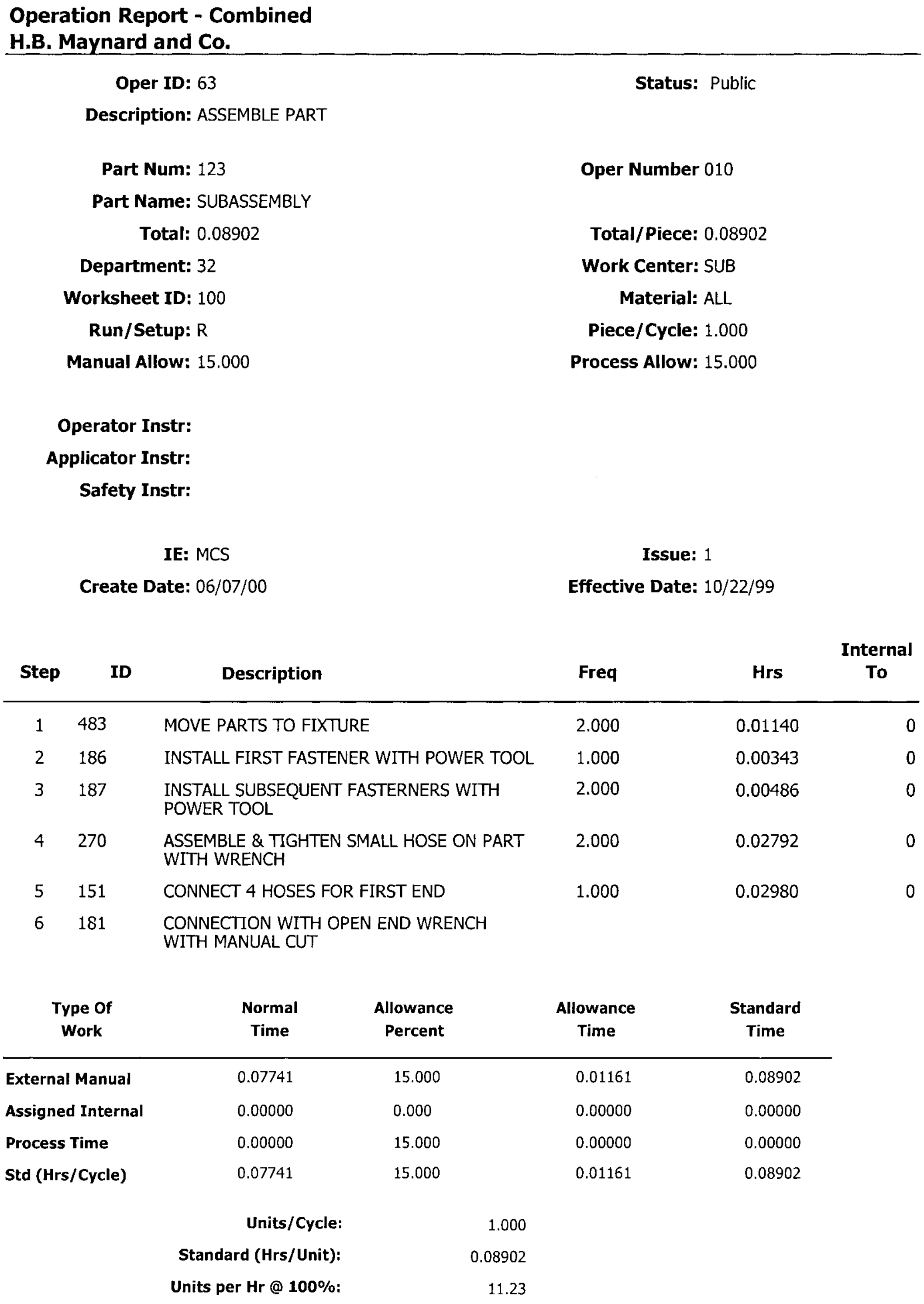
Product: EASEWorks

Company: EASE Inc.

Measurement Systems: MTM-based EASE Macros

EASEWorks is a suite of client/server software designed to provide manufacturing and service companies with the ability to develop standard data and work standards. The software is preloaded with a library of standard data and enables users to create standard data or use existing data to develop work standards.

Additional features include work instructions, and the ability to link data to ERP/MRP and other business systems. Figure 5.6.3 shows the first 17 method steps of an example standard developed with EASEWorks.



Operation Report - Combined
H.B. Maynard and Co.

Oper ID: 63
Status: Public
Description: ASSEMBLE PART

Part Num: 123
Oper Number 010
Part Name: SUBASSEMBLY
Total: 0.08902
Total/Piece: 0.08902
Department: 32
Work Center: SUB
Worksheet ID: 100
Material: ALL
Run/Setup: R
Piece/Cycle: 1.000
Manual Allow: 15.000
Process Allow: 15.000

Operator Instr:
Applicator Instr:
Safety Instr:

IE: MCS
Issue: 1
Create Date: 06/07/00
Effective Date: 10/22/99

Step	ID	Description	Freq	Hrs	Internal To
1	483	MOVE PARTS TO FIXTURE	2.000	0.01140	0
2	186	INSTALL FIRST FASTENER WITH POWER TOOL	1.000	0.00343	0
3	187	INSTALL SUBSEQUENT FASTERNERS WITH POWER TOOL	2.000	0.00486	0
4	270	ASSEMBLE & TIGHTEN SMALL HOSE ON PART WITH WRENCH	2.000	0.02792	0
5	151	CONNECT 4 HOSES FOR FIRST END	1.000	0.02980	0
6	181	CONNECTION WITH OPEN END WRENCH WITH MANUAL CUT			

Type Of Work	Normal Time	Allowance Percent	Allowance Time	Standard Time
External Manual	0.07741	15.000	0.01161	0.08902
Assigned Internal	0.00000	0.000	0.00000	0.00000
Process Time	0.00000	15.000	0.00000	0.00000
Std (Hrs/Cycle)	0.07741	15.000	0.01161	0.08902

Units/Cycle: 1.000
Standard (Hrs/Unit): 0.08902
Units per Hr @ 100%: 11.23

FIGURE 5.6.1 Engineered labor standard developed with MOST Data Manager.

COMPUTERIZED LABOR STANDARDS

```
MTM-LINK          R5815B      SUMMARY OPERATION STANDARD REPORT      Requested By MMMM  Time 13.31.54  Date 06/05/2000      Page   1

Part.....: MLUCOIL                 Coil                                                 Originated: 08/22/1996 By MMMM
Operation: 10                      Wind coil on Bache Model AZ129                       Revised...:   /  /     By      Letter:
Dept.....: MLUT                    Release Status: R                                                                  Code..:
Machine..: AT                      Study Code....:                                           Standard Minutes - Setup:
Tooling..:                                                        Units Per Hour:   71.73                       Run..:       0.837
Est. Plan:                                                   ***** STANDARD UPDATED *****
Allowance: -----Setup Manual------ % --  -----Setup Process----- % --     ------Run Manual------- % --  ------Run Process------ % --
        1. Setup Manual Default:  15.00  Setup Process Deflt :  12.00     Run Manual Default  :  15.00  Run Process Default :  12.00
                    Added Total:  15.00           Added Total:  12.00              Added Total:  15.00           Added Total:  12.00

                                                                               Group                                       Extended
      Element   Description                                                   Markers           MUs         Frequency        MUs

                                                            --- RUN ---

  1  MLCLWP001S  Prepare machine for winding: Change wire, gage, test, and    N                 2560           .0040             10
                 trim end.

  2  MLCLWL001U  Load bobbin in winding machine.                                                2030                           2030
                                                                                                 278P                           278

  3  MLCLWM001S  Wind coil on Bache.                                                            8250P                          8250S

  4  MLCLWF001U  Tape and finish coil.                                                          3000                           3000M

                 **** PROCESS COMPLETION ****                                                                                  5250

  5  MLCLWU001U  Unload wound coil and finish.                                                  1700                           1700


                                                       Total RUN MUs -Manual         6740 With Allowance         7751
                                                                     -Process        5528 With Allowance         6191
                                                                                 Total Standard RUN Time        13942 MU
                                                                                               Crew Size         1.00
                                                                                          Cycle Quantity         1.00
                                                                                  Unit Standard RUN time        13942 MU
                                                                                                               50.191 Seconds
                                                                                                                 .837 Minutes
                                                                                                               .01394 Hours
                                                                                                                1.394 Hours/100
                                                                                                                13.94 Hours/1000
                                                                                                              139.420 Hours/10000
                                                                                          Units Per Hour        71.73

MAI   0 Percent          RMB   0 Percent   GRA   0 Percent   POS   0 Percent         PROC  44 Percent

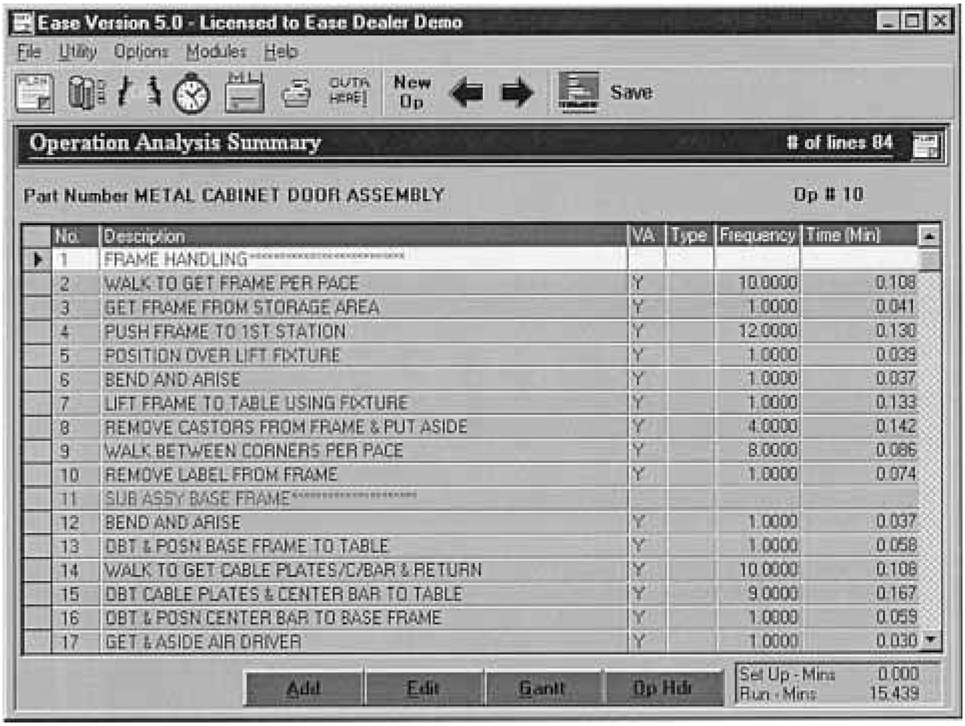
 Group     Group Desc                 Standard
   N    Non value added                  0.001
```

Engineered labor standard created with MTM-LINK.

Product: VIA, Productivity Measurement

Company: IET, Inc.
Measurement Systems: MTM GPD (general purpose data)

Via, Productivity Measurement™ is a computerized program that directs the development, organization, and management of standard data for work measurement. The system is designed for engineers and technicians who have a large number of standards to create or maintain. Via, Productivity Measurement is a hierarchical program that allows standard data of any format to be entered into the system or developed within the system using the work standard generator. The data can then be used to develop work standards and linked to allow shared data, quick standard development, and mass updating. All data entry is through simple menu selections and electronic check sheets.



Part Number METAL CABINET DOOR ASSEMBLY Op # 10

No.	Description	VA	Type	Frequency	Time (Min)
1	FRAME HANDLING*************************				
2	WALK TO GET FRAME PER PACE	Y		10.0000	0.108
3	GET FRAME FROM STORAGE AREA	Y		1.0000	0.041
4	PUSH FRAME TO 1ST STATION	Y		12.0000	0.130
5	POSITION OVER LIFT FIXTURE	Y		1.0000	0.039
6	BEND AND ARISE	Y		1.0000	0.037
7	LIFT FRAME TO TABLE USING FIXTURE	Y		1.0000	0.133
8	REMOVE CASTORS FROM FRAME & PUT ASIDE	Y		4.0000	0.142
9	WALK BETWEEN CORNERS PER PACE	Y		8.0000	0.086
10	REMOVE LABEL FROM FRAME	Y		1.0000	0.074
11	SUB ASSY BASE FRAME*********************				
12	BEND AND ARISE	Y		1.0000	0.037
13	OBT & POSN BASE FRAME TO TABLE	Y		1.0000	0.058
14	WALK TO GET CABLE PLATES/C/BAR & RETURN	Y		10.0000	0.108
15	OBT CABLE PLATES & CENTER BAR TO TABLE	Y		9.0000	0.167
16	OBT & POSN CENTER BAR TO BASE FRAME	Y		1.0000	0.059
17	GET & ASIDE AIR DRIVER	Y		1.0000	0.030

Set Up - Mins 0.000
Run - Mins 15.439

FIGURE 5.6.3 Partial engineered labor standard created with EASEWorks.

All production data including performance, production loss, and reason codes are managed within the system to allow simple and flexible reporting. The users of the system can generate predefined reports automatically or they can generate specific reports varied by product, process, date range, shift, reason code, and so on. Simple electronic check sheets allow for quick reporting and simple customization.

An example time standard created with VIA, Productivity Measurement is shown in Fig. 5.6.4.

THE FUTURE

Computerized standards systems will become even more relevant in the future. As computers become less expensive and computerized standards systems become increasingly powerful and easy to use, more organizations will be able to economically justify computerized systems. With the inclusion of packaged standard data (see Chap. 5.3) and easy-to-use software packages, many companies will recognize the benefits of a computerized standards system. In addition, handheld computers and personal digital assistants will continue to grow in popularity, and software will more regularly be used on the shop floor, thereby improving the process of creating standards and saving valuable time. Since computers will continue to progress in their ability to document, control, and drive manufacturing processes and service activities, computerized labor standards will be used more frequently to feed these systems.

COMPUTERIZED LABOR STANDARDS

Units = Seconds

Part Number:
Description: REAM HOLES IN WOOD PART (Seq.)
Type:

Activity:	Al Lathe—ream holes in wood block (Seq.)		
	01Obtain five parts from cart (Seq.)		4.32
	Total Operation Time:		4.32
	02 Ream 1st part (Seq.)		
	E1 Place part in fixture		1.08
	E2 Cycle machine		3.24
	E3 Remove part from fixture		1.08
		Total Operation Time:	5.40
	03 Ream 2nd part (Seq.)		
	E1 Place part in fixture		1.08
	E2 Cycle machine		3.24
	E3 Remove part from fixture		1.08
		Total Operation Time:	5.40
	04 Ream 3rd part (Seq.)		
	E1 Place part in fixture		1.08
	E2 Cycle machine		3.24
	E3 Remove part from fixture		1.08
		Total Operation Time:	5.40
	05 Ream 4th part (Seq.)		
	E1 Place part in fixture		1.08
	E2 Cycle machine		3.24
	E3 Remove part from fixture		1.08
		Total Operation Time:	5.40
	06 Ream 5th part (Seq.)		
	E1 Place part in fixture		1.08
	E2 Cycle machine		3.24
	E3 Remove part from fixture		1.08
		Total Operation Time:	5.40
	07 Aside five parts (Seq.)		3.60
		Total Operation Time:	3.60
		Total Activity Time:	34.92
		Total Value-Added Time:	34.92

FIGURE 5.6.4 Engineered labor standard created with VIA, Productivity Measurement.

The most powerful addition to the capabilities of computerized labor standards systems in recent years has been expert system technology. Expert system technology allows nonexperts to arrive at the same, logical conclusion that an expert would arrive at through a series of logical steps. This technology has been adopted and is currently being used in some existing labor standards systems. The use of expert systems further automates and speeds up the process of standards development. This trend will continue as the systems become more powerful and easier to use. The potential to link this technology with that of voice recognition may lead to an even higher state of automation and efficiency. Imagine an industrial engineer on a shop floor describing the work or answering questions and having the standards being developed simultaneously. This would virtually eliminate any of the non-value-added clerical work involved with standards development.

With the availability of affordable, easy-to-use computerized labor standards systems, any labor-intensive organization can benefit and profit from the use of such programs. The benefits and return on investment to the organization are easily justified, and the time saved will allow productivity to continue to increase at facilities that implement and effectively use computerized labor standards systems.

FURTHER READING

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SUGGESTED WEB SITES

www.hbmaynard.com
www.mtm.org
www.easeinc.com
www.ieteng.com

BIOGRAPHIES

Jeffrey Peretin is a senior account manager with H. B. Maynard and Company, Inc., of Pittsburgh, Pennsylvania. He has extensive experience in the area of metal fabrication and assembly. Since joining Maynard, he has successfully managed projects in a wide variety of areas, including retail and distribution, automotive fabrication, and assembly. Peretin holds a bachelor's degree in industrial engineering from the University of Pittsburgh.

Gregory Smith is an account manager with H. B. Maynard and Company, Inc., of Pittsburgh, Pennsylvania. His experience with Maynard, over a period of four years, has consisted primarily of developing engineered labor standards and working with computerized labor standards systems domestically and internationally in a broad range of industries. In addition, he has trained hundreds of industrial engineers in this discipline. Smith holds a bachelor's degree in industrial management from Grove City College.

Source: MAYNARD'S INDUSTRIAL ENGINEERING HANDBOOK

CHAPTER 5.7

IMPLEMENTATION AND MAINTENANCE OF ENGINEERED LABOR STANDARDS

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Setting standards is only the first step to improving productivity. There must be a coordinated, organized plan for implementing and enforcing standards. This includes communicating standards to the shop floor employees, managing performance through the operations management structure, and implementing new standards throughout the organization by coordinating labor standards with financial costing systems.

Maintaining a work measurement and performance management program is critical to realizing long-term benefits. A planned and regularly scheduled standards auditing program is the keystone to program maintenance. This chapter discusses the implementation of labor standards after their initial development and the maintenance required to make those standards a long-standing success.

INTRODUCTION

Webster's Ninth New Collegiate Dictionary defines a *standard* as "something that is set up and established by authority as a rule for the measure of quantity, weight, extent, value, quality or time." Labor standards are used as a guide to evaluate the amount of time that should be taken to perform an operation by an average-skilled operator following a prescribed method and working at a normal pace.

The Use of Labor Standards

Companies use labor standards for several reasons. From a shop floor perspective, standards can be used to help determine staffing levels and distribution, measure employee performance, influence and control incentive systems, provide detailed methods documentation, and/or provide employees and supervisors with output goals. From a management perspective, standards provide measurement data for staffing and production, scheduling, reward and discipline, and forecasting. From a financial perspective, standards provide a yardstick for success as well as data for costing, and ultimately decisions affecting margin and profitability. The impact of properly engineered labor standards are illustrated in the following examples:

1. *Product cost assessment*
   Accounting procedures in most companies use labor standards as a basis for developing product costs. Accurate standards allow products to be properly costed and budgets to be realistically set.
2. *Scheduling and production flow analysis*
   Labor standards can be used for machine load planning and for scheduling of orders through the shop. Properly installed labor standards, along with a good maintenance program, will allow overtime to be minimized, and promote timely production and efficient facility utilization.
3. *Labor planning*
   Regulating labor totals to schedule workload is a necessary step in securing satisfactory performance. Properly installed and maintained labor standards will ensure the confidence of management and worker alike, providing a common ground for business decisions regarding staffing.
4. *Labor variance tracking and elimination*
   Properly engineered and installed labor standards provide management with a solid basis for setting production expectations. These expectations can then be used for budgeting. Variance from any production goal or budget will indicate problems in the short run with performance, and trends in labor variance will indicate more systematic problems in the long run. Identifying these variances will allow management to take action not only to improve performance, but to make the overall production system more efficient.
5. *Cost estimates*
   Standard data lends itself to the development of estimates for sales purposes. Accurate labor costs are requisite for proper marketing decisions. The traditional method of apportioning factory overhead and burden on the basis of direct labor makes this accuracy that much more significant. Recent trends in activity-based cost (ABC) accounting will reduce this impact.
6. *Cost reduction possibilities*
   In many cases, new equipment justification, layout revisions, and methods changes involve comparisons with existing standards. Product design improvements require cost estimates. Accurate labor standards will increase estimate accuracy, and give management a powerful justification tool.

Background information on engineered labor standards can be found in Chap. 5.1, Measurement of Work and Chap. 5.2, Purpose and Justification of Engineered Labor Standards. The methods for developing labor standards are presented in Chap. 5.3, Standard Data Concepts and Development and Chap. 5.4, Developing Engineered Labor Standards.

This chapter provides guidance on standards application for managing a business, or "tells you what to do with the standards once you have them." Standards development, no matter how expertly accomplished, does not provide a manager with information crucial to running his or her business. The interpretation of, belief in, and use of standards mark the transformation of data into management information and ultimately knowledge necessary for wise decision making. The goal of this chapter is to explain what is necessary to make this transformation take place and thrive.

IMPLEMENTATION OF ENGINEERED LABOR STANDARDS

Definition of a Successful Implementation

A successful implementation of engineered labor standards is simply defined as having all levels of the organization believe in and use standards on an ongoing basis to run the business and make wise business decisions. This happens only with the full support of the organization from the top down. The simplest way to ensure trust at all levels is an ongoing commitment to communication and involvement. The steps necessary for making this happen are outlined in the following sections.

The Link Between Development and Implementation

A certain level of credibility should have already been established prior to implementing a standards program. A proper development program will have involved the employees on the floor as domain experts, the supervisors as sources of information, and upper management as guides and decision makers. As such, everyone concerned will be aware of the program prior to any impact on the day-to-day workings of the company, and a level of commitment will have already been established. This is important to the implementation program because a certain level of credibility should already be in place. This communication and involvement must then continue in the rollout or implementation of the standards.

Standards Implementation

There are two areas in which engineered standards must be implemented: the shop floor and the office. The individual areas will be discussed separately.

Shop Floor Implementation. Shop floor implementation is defined by a systematic approach ensuring that three broad questions are fully addressed: (1) Who will be affected by the standards? (2) What will be required to implement the standards? and (3) How will the standards be implemented? Note that while the term *shop floor* is used in this chapter, the same technique can be applied to service, white collar, or any other standards implementation. This technique is in no way limited to manufacturing environments.

Areas Affected

Industrial Engineering. Full-time dedication of engineering resources is important to a successful labor standards program. Part-time involvement tends to diminish the impact of the program. The momentum of one full-time engineer will exceed that of two half-time engineers. Part-time support may be necessary due to resource constraints, but should be avoided.

Industrial engineering support must be readily accessible to answer questions. It is typical to expect questions regarding noncyclical activities. For instance, 15 fasteners may be required to assemble each part covered by a standard. Reloading these parts to a workplace may take place every 1500 fasteners. Employees will need reassurance that this has been accounted for in the standard.

Hourly Employees. Hourly employees are particularly sensitive to a change in labor standards when an incentive system is in place. Communicating the reasoning behind any changes is a prerequisite to gaining the acceptance of hourly employees. As new and/or updated standards often mean changes (sometimes drastic changes) for shop floor employees, they must understand that these changes are based on business facts and objective reasoning.

Shop Floor Supervision. The role of the supervisor in any implementation is as a communicator. The supervisor must be at the core of the team that ensures employees understand the standards. It is critical that supervisors from the shop floor take an active part in the validation of standards prior to implementation. Validation is requisite to the supervisors believing in the information that the standards provide. Belief in the standards will allow management to more effectively supervise and manage the performance of the employees.

Union Representation. In many situations where labor standards are used, the employees will be represented by organized labor. In this situation it is important to involve the union representation in the implementation process. Contract language must be respected. This will often include any Right to Change clause in the negotiated contract. The union representatives must understand the methods used to develop the standards and also understand the ramifications of any new standards.

Resources Required. Sufficient resources must be allocated to the labor standards project to ensure that the time between the start of the program and the full implementation of labor standards does not exceed a reasonable time. A *reasonable time* depends on several variables for each department. Among these is the variability of product through the department, number of employees represented, number of separate workstations, and number of standards to be implemented. The resources required can be split into four general categories: technical resources, reporting and performance management, communication, and training.

Technical Resources. Technical resources will include personnel, equipment, and procedures. Personnel such as industrial engineers, supervisors, shop floor representatives, and any required programming personnel must be dedicated to the implementation process to facilitate a steady rollout and encourage a long-term belief in the system.

Equipment will include any new fixtures identified during the methods improvement phase of standards development, any refurbishing of machines required to bring their cycle times up to standard, and any new tools for reporting and communication. The latter could represent everything from a schedule board to a new program for performance reporting.

Procedural changes required to facilitate the implementation of the new standards will need to be instituted in a methodical, logical, and clearly defined manner. While much of this will involve training and communication, the technical details of the process must be developed first.

Performance Management and Labor Reporting. While it is crucial that timely and accurate data be collected from the floor, it is even more crucial that management be able to view, analyze, and interpret this data on an ongoing basis. The process of transforming data into useful information in this manner forms the foundation for performance management. Further information on managing to a standard can be found in Chap. 2.4, Performance Management: A Key Role for Supervisors and Team Leaders.

TOOLS: The most important tools to the supervisor are efficiency or productivity reports. There are several variations of and uses for these reports. Two of the most common uses are incentive pay and performance. An example of a performance report is illustrated in Fig. 5.7.1.

This report indicates the actual results from a production period for a series of work centers versus the expected results for the same period. In this particular case

Area	Actual					Earned (Standard) Hours
	Net Production	Run Hours	Delay Hours	Total Hours	Scheduled Hours	
	(A)	(B)	(C)	(D)	(E)	(F)
Stamping	12000	410	40	500	500	396
Finishing	10000	490	40	535	535	500
Painting	11000	800	80	900	900	880
Assembly	12000	1500	135	1650	1600	1320
Packing	12000	55	10	65	65	57.6
Total	12000	3255	305	3650	3600	3153.6

Area	Control Indices				
	Performance Factor	Coverage Factor	Productivity Factor	Delay Factor	Utilization Factor
	(F/B)	(B/(D-C))	(F/D)	(C/D)	((D-C)/D)
Stamping	97%	89%	79%	8%	92%
Finishing	102%	99%	93%	7%	93%
Painting	110%	98%	98%	9%	91%
Assembly	88%	99%	80%	8%	92%
Packing	105%	100%	89%	15%	85%
Total	97%	97%	86%	8%	92%

FIGURE 5.7.1 Management production report.

Column A indicates the measure used (net pieces produced).

Column B represents the run hours, or hours during which pieces were actually being processed.

Column C represents the hours charged to delay.

Column D represents the total hours worked at each station. It represents not only hours spent on standard (column B) and reported delay time (column C), but also unreported delay time and nonstandard hours.

Column E indicates the scheduled hours for the area.

Column F represents the earned (or standard) hours for the production quantity during the time period. This is calculated by multiplying the standard time per piece by the total pieces produced.

The control indices listed on the performance report are the most important tools management has for controlling production. This is true in any environment: union or nonunion, piecework or day work. Standards provide a valuable data source, but without proper interpretation, application, and feedback, little value will ever be realized from a standards development project. Listed here are the most common control indices and guidelines and their interpretation.

PERFORMANCE: Performance measures the actual hours worked on a task in relation to the standard hours allowed for that task. Performance of less than 100 percent indicates substandard performance. Performance of greater than 100 percent indicates performance above what would be expected of an average-skilled, trained operator working at normal pace. Either situation should be immediately analyzed by the supervisor. Trends in both below-normal and above-expected performance will often signify a need for retraining in either work methods or time reporting procedures.

$$\text{Performance} = \frac{\text{Standard Hours Earned}}{\text{Actual Hours Spent on Standard Time}}$$

The specific instances where performance levels would indicate a need for research can be graphically represented as shown in Fig. 5.7.2. The actual control limits will vary depending on the accuracy specified when designing the standards. For more information on choosing accuracy levels, see Chap. 5.3.

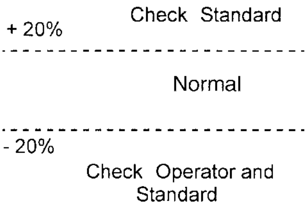


FIGURE 5.7.2 Performance control limits.

COVERAGE: Coverage measures the efforts of the IE department to measure all shop floor activities and supervisors to schedule work. This index can be affected by any off-standard production runs (i.e., trial runs, experiments). Acceptable coverage should exceed 90 percent for a weekly reporting period. Setup times should be measured for machine controlled operations when coverage falls below 90 percent in those areas for a given production period (typically a week).

$$\text{Coverage} = \frac{\text{Actual Hours on Standard Time}}{\text{Total Productive Hours Minus Delay Time}}$$

PRODUCTIVITY: Productivity measures actual production against the overall production goal. It represents the combined efforts of labor and management. Evaluation of productivity should take into account utilization and performance indices.

$$\text{Productivity} = \frac{\text{Earned Hours}}{\text{Total Hours} - \text{Unmeasured Hours}}$$

DELAY: Delay measures the percentage of total time that is not spent on productive activities. Time reported to delay must be closely monitored by management. Delay time indicates activities that should not occur on a regular or recurring basis. Companies will typically have several different delay codes that are used (i.e., machine down, materials shortage, meetings). The aggregate delay time should typically be less than 5 percent. Note that most standards have an allowance for minor unavoidable delays built in. It is important that delays covered by this allowance not be reported as a separate delay. This typically means that any delay less than 6 minutes in duration is not reported as a separate delay.

$$\text{Delay} = \frac{\text{Delay Hours}}{\text{Total Hours}}$$

UTILIZATION: Utilization measures the percentage of time a worker spends on productive, standard work in relation to overall clocked hours.

$$\text{Utilization} = \frac{\text{Total Hours Minus Delay Time}}{\text{Total Hours}}$$

The supervisor must then ensure that reporting from the shop floor is consistent and accurate. Some implementations fail because data collected from the floor does not accurately depict what is happening at any given time.

Ensuring accurate data collection ranges from simply making sure that time cards are filled out properly to guaranteeing that proper maintenance activities are performed on gauges and readers to make sure they are working properly. The exact nature of data collection will vary depending on the nature of the process under consideration and the degree of technology required for reporting purposes. Typically, longer cycle tasks will require less complicated reporting processes. For example, a plant that produces 10 grommets per day will require less sophistication than one that produces 100,000 widgets in the same time period. Typically, the more sophistication required, the more computerization required. This can range from a hand-calculated matrix at the extreme simple end of the spectrum to a complete enterprise resource planning (ERP) system at the opposite end. Reporting should be done as frequently as resources permit, but at least on a weekly basis, preferably daily. Timely and frequent feedback minimizes the number of corrective actions required, and maximizes the effectiveness of any such actions.

Communication. Communication is the key ingredient to a successful program in any environment. Upper management must visibly support the initiative for long-term success to be possible. This support will flow through the entire organization if upper management communicates that support.

Upper management should first meet with any union representation to explain the program and any foreseen impact on a negotiated labor contract. It is vitally important for the union representation to support the new system if the shop floor employees are to be expected to perform to the new standards.

The plant manager should hold an informational session with all affected employees prior to implementation. This session should cover the following topics:

1. The reason for the program
2. Confirmation that union representation has been notified of the program and any effect on a negotiated labor contract
3. Estimated time of program
4. Departments affected
5. Selection process for a technical team to support the program
6. Introduction of the team responsible for data development and labor standards development.

For larger facilities where meetings are not possible, the plant manager should post plantwide memos, or display videotaped messages outlining the preceding six items and hold a departmental meeting with the first department to be scheduled for new labor standards to allow for a question and answer session.

Resources should be dedicated to ensure that full interaction and communication with affected employees is possible throughout the implementation process. These resources should include both industrial engineering and shop floor management or supervision. It is crucial that supervision take ownership of the standards, it cannot appear as if labor standards belong to the engineering group. Industrial engineering must be a support function to the standards, but management must take full ownership.

Training. Supervisors should have a thorough understanding of the methods represented by the standards and also understand the output that should be expected by an employee working to standard. It is important to note that all tools should be ready and supervisors trained in their use prior to implementation. This may require a training session for shop floor supervisors who are not used to managing performance.

Implementation Method. Employee acceptance requires that they see the program progressing at a good pace. There should be no delay in implementing standards in one area after all concerns in the previous area have been addressed. This will show the shop floor employees that management is committed to the program and that they consider it a priority.

Pilot Area. The implementation of standards works best when the new/updated standards are first implemented in a pilot area. The selection and implementation of this area will be covered in later sections.

Selection of Pilot Areas. An area or department should be selected as the pilot project rather than attempting to cover an entire facility at one time. This will allow the engineers to have a quick implementation and success prior to rolling out the program into other areas. The pilot area should be selected based on a combination of the following factors.

PROBABILITY OF SUCCESS: The pilot area is an excellent opportunity for establishing initial success. This will build a reputation for credibility that will continue through later steps and areas. Momentum is a very important factor in a successful implementation program. Quite often a success in the pilot area will enable the team to weather any rough spots in successive departments. Some questions that should be asked include, "Are the employees in this area supportive?" "Is supervision in this area experienced and trusted?" "Have there been any ongoing disciplinary issues in this area?"

COMPANY COST IMPACT: The pilot area should have a noticeable impact on company costs so that progress can be readily identified. The implementation of properly engineered standards will often result in a decrease in standard costs. Some questions that should be asked include, "How much of an impact will a 10 percent to 15 percent reduction in labor costs in the pilot area have on the total product costs?"

SCHEDULE FACTORS: Similar to company cost impact, the pilot area should also have a significant impact on the process flow in the department. At the same time, a pilot area should not be scheduled for reengineering in the near future. The pilot area should be able to show sustainable results. Some questions that should be asked: "Is this a bottleneck department?" "Would an improvement in cycle time have a significant effect on the overall product schedule?" "Is engineering investigating the purchase of additional equipment to increase productivity?"

PERFORMANCE FACTORS: The pilot area should have employees that are fully trained and able to follow standard methods. Employees should not feel like they have to work harder to meet the new standards. Some questions that should be asked include, "Does this area have problems achieving current performance to schedule goals?" "Do the employees seem to constantly exceed their performance goals?"

NEW PROCESS OR PRODUCT LINE: It is always beneficial to install standards in a new area. This will allow employees to attain the standard and to establish the credibility of the measurement. This will be of great benefit when addressing any concerns over the comparison of previous standards to new ones in successive areas and/or products. Some questions that should be asked: "Is new equipment being considered since this facility has problems achieving current performance to schedule goals?" "Is the company management considering 'farming out' work since full capacity appears to have been reached?"

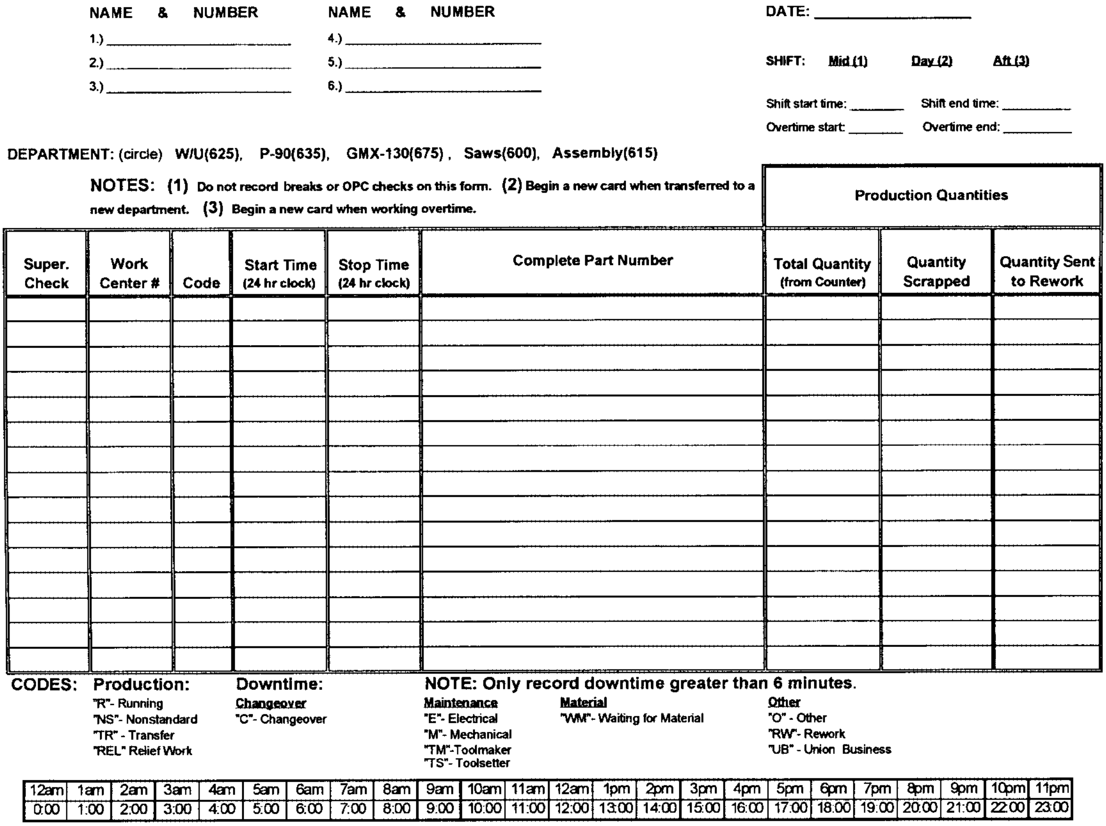
Implementation in Pilot Area. After the selection of the pilot area, implementation can begin. This will involve the following steps:

DEVELOP INFRASTRUCTURE: Prior to implementation, all components required to make standards successful should be in place. This includes

Time and production reporting systems. Any new time cards, reports, and/or counting devices or procedures should be in place prior to implementation. A typical operator production reporting card is shown in Fig. 5.7.3. Similarly, any reports necessary for supervision to manage the area should also be developed.

New equipment. Any new equipment that is required for standards implementation (signals, counting devices, etc.) should be installed and ready for operation prior to implementation of the standards.

PROVIDE METHODS TRAINING: If any new methods were developed in the course of standards development, all operators affected by the changes should be trained in the new method prior to implementation of the standards. All operators should be able to perform tasks according to prescribed methods and without hesitation. This may require a period of practice. Sufficient time should be allowed for all operators to familiarize themselves with the prescribed methods before implementing standards.



NAME & NUMBER
1.) ____________
2.) ____________
3.) ____________

NAME & NUMBER
4.) ____________
5.) ____________
6.) ____________

DATE: ____________

SHIFT: Mid (1) Day (2) Aft (3)

Shift start time: ________ Shift end time: ________
Overtime start: ________ Overtime end: ________

DEPARTMENT: (circle) **W/U(625), P-90(635), GMX-130(675), Saws(600), Assembly(615)**

NOTES: (1) Do not record breaks or OPC checks on this form. **(2)** Begin a new card when transferred to a new department. **(3)** Begin a new card when working overtime.

						Production Quantities		
Super. Check	Work Center #	Code	Start Time (24 hr clock)	Stop Time (24 hr clock)	Complete Part Number	Total Quantity (from Counter)	Quantity Scrapped	Quantity Sent to Rework

CODES: **Production:**
"R"- Running
"NS"- Nonstandard
"TR" - Transfer
"REL" Relief Work

Downtime:
Changeover
"C"- Changeover

NOTE: Only record downtime greater than 6 minutes.

Maintenance
"E"- Electrical
"M"- Mechanical
"TM"-Toolmaker
"TS"- Toolsetter

Material
"WM"- Waiting for Material

Other
"O" - Other
"RW"- Rework
"UB" - Union Business

12am	1am	2am	3am	4am	5am	6am	7am	8am	9am	10am	11am	12am	1pm	2pm	3pm	4pm	5pm	6pm	7pm	8pm	9pm	10pm	11pm
0:00	1:00	2:00	3:00	4:00	5:00	6:00	7:00	8:00	9:00	10:00	11:00	12:00	13:00	14:00	15:00	16:00	17:00	18:00	19:00	20:00	21:00	22:00	23:00

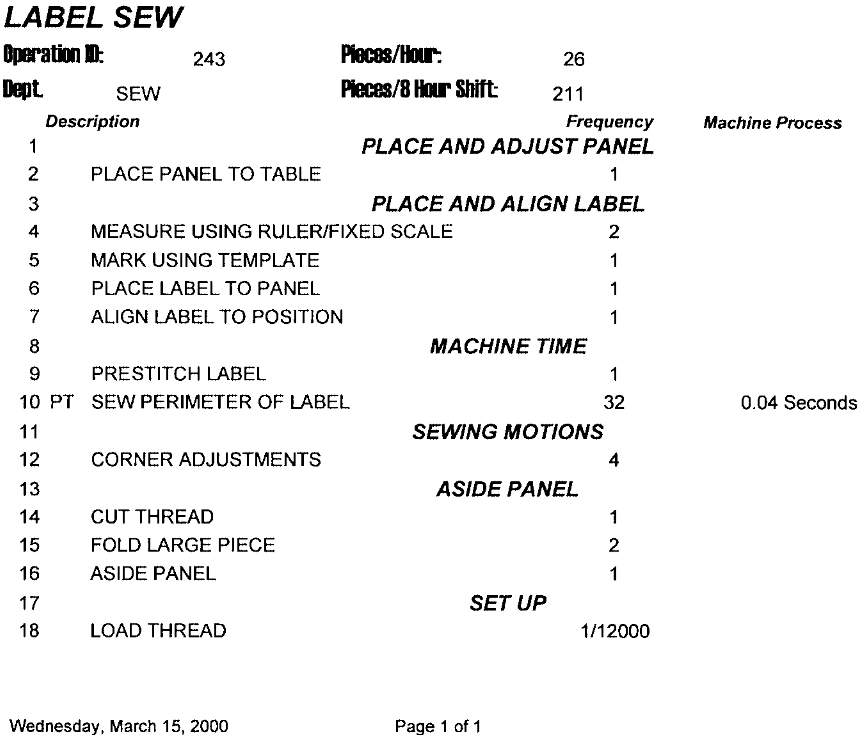
FIGURE 5.7.3 Operator production reporting card.

IMPLEMENTATION AND MAINTENANCE OF ENGINEERED LABOR STANDARDS

PROVE STANDARDS: Standards in each area must be accepted by the shop floor employees as valid measures. This is done through an initial validation. Employees must believe that all aspects of the job have been accounted for. Methods on which the standards were developed should be posted at each affected station and distributed to all employees in the affected area.

A posting of methods with adequate opportunity for question and answer will address this. An example of a typical methods sheet is depicted in Fig. 5.7.4. Implementation and validation of standards by shop floor employees must not be taken lightly. This is one of the most crucial aspects of a successful implementation. Care should be exercised to validate standards based on the form of measurement used. For example, if a predetermined system has been used to develop standards, using a stopwatch to validate the standards will not address any concerns. In a predetermined measurement system, work method was used to develop the standards, and documented work method should be validated. This is accomplished by a careful comparison of the method documented and used to develop the time standard with actual shop floor conditions. Extra care must be taken to ensure that "infrequent" activities are accounted for. In the illustrated example, the loading of the thread is an infrequent activity. Any variances between documented and actual conditions must be addressed at this time. This may result in method improvements on the shop floor, additional training for operators, or, less frequently, some modification of the standard. Representatives from the industrial engineering group, supervision, and upper management should take part in this process. Workers must know that the new standards are being taken seriously. The workers must be assured that they have input into the validation of the methods studied, and their concerns must be addressed during this period.

Standards should be validated with supervisors in the same manner that they are validated with shop floor employees—in a manner consistent with the method of measurement used. A



LABEL SEW

Operation ID: 243 **Pieces/Hour:** 26

Dept. SEW **Pieces/8 Hour Shift:** 211

	Description	Frequency	Machine Process
1	***PLACE AND ADJUST PANEL***		
2	PLACE PANEL TO TABLE	1	
3	***PLACE AND ALIGN LABEL***		
4	MEASURE USING RULER/FIXED SCALE	2	
5	MARK USING TEMPLATE	1	
6	PLACE LABEL TO PANEL	1	
7	ALIGN LABEL TO POSITION	1	
8	***MACHINE TIME***		
9	PRESTITCH LABEL	1	
10 PT	SEW PERIMETER OF LABEL	32	0.04 Seconds
11	***SEWING MOTIONS***		
12	CORNER ADJUSTMENTS	4	
13	***ASIDE PANEL***		
14	CUT THREAD	1	
15	FOLD LARGE PIECE	2	
16	ASIDE PANEL	1	
17	***SET UP***		
18	LOAD THREAD	1/12000	

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FIGURE 5.7.4 Operation method report.

predetermined system focuses on work method, and the validation should involve the same procedure. There should be minimal adjusting of standards at this point; the majority of validation will have occurred during the data development process. It is important, however, to give supervisors and upper management the opportunity to perform additional validation. While minimal correction may be required, the gains to be realized from a management team that fully believes in the accuracy of the standards will make any investment well worth the time. This will be especially beneficial when addressing the concerns of the workers during the initial implementation period. Validation with the management team should take place prior to any shop floor implementation.

ENSURE ACCOUNTABILITY: After validation has addressed any concerns over methods, standards must be enforced. The test area should show that standards are fair and consistently attainable. This may take a period of time, especially in areas where methods have been changed or standardized, or where prior standards were loose.

Rollout. After the test area has shown success, further departments should be covered in the same manner. This will require increasing levels of support as each new area is converted to the new standards. Building on the success gained in the pilot area, a similar approach should be followed in each subsequent area in which standards are implemented.

Review, Follow-up, and Modifications (Reporting and Feedback). Following the issuance of standards to the shop floor, it is normal to expect some period of time when performance to standard does not meet expectations. This could be because the new labor standards are lower than the previous standards, or when no prior labor standards exist, the operators are not used to producing at the higher output level. In either case, the standards will come under close scrutiny by both the operators and factory supervision. It will be important to convince both groups that the standards are realistic and achievable.

This can best be accomplished through the use of a feedback system, where the following steps are used:

1. The operator, after deciding the standard does not accurately reflect the work content, work area layout, or other conditions, will notify his or her supervisor.
2. The supervisor will review the posted method description for any missing or misapplied elements. Should any be found, the industrial engineering group should be notified to change the standard.
3. The supervisor will review the method being used by the operator to ascertain whether they are following the method prescribed by the standard.
4. The supervisor will check any equipment process time(s) to make sure they are within the specifications set forth in the standard. In the same manner, the supervisor will check the operation of the equipment to ensure that it is within the specifications set forth in the standard. If they are not, the industrial engineering and maintenance groups should be notified so that root causes can be determined and corrected.
5. The supervisor will check the sequence of method steps.
6. The supervisor will then check for extra steps added by the operator, determining whether they are necessary steps.
7. The supervisor will evaluate the operator's skill level: good, average, fair, poor.
8. The supervisor will then evaluate the operator's effort level: good, average, fair, poor.
9. Should the preceding steps not result in a root cause being identified, the supervisor will investigate and decide whether the conditions presented by the employee are sufficient to justify assistance in getting a change in the appropriate standard(s). There should be a potential to obtain at least a 5 percent variance from the existing standard to justify requesting any investigation by industrial engineering.
10. Industrial engineering will schedule a standard review. The review should first look at the application frequency, then work content and process times, and finally, overall operational cycle time.

11. Following the review of the standard, the industrial engineer should discuss the results of the standards review with the supervisor, employee, and union representative (if required by contract).
12. Any identified changes to the standard will be carried out by industrial engineering in a timely manner.

Rarely will a change progress to the industrial engineering group as long as periodic standards maintenance is performed. This is highlighted in the next part of this chapter.

Office Implementation. Accuracy and usefulness are the two cornerstones of a managerial implementation. A proper implementation involves showing management that the standards will provide them with accurate information that will enable them to make good business decisions. A proper implementation also guarantees that a reporting system is in place to ensure that management receives this information in a timely and usable format.

Accounting. One of the most important areas for a successful implementation of engineered standards is the financial side of the business. Active participation by cost accounting will be crucial to fully realizing the benefits of engineered labor standards. For instance, while reduced labor costs will be realized through better utilization and management of labor resources, the full benefits of engineered labor standards are much more wide-ranging.

Cost Implications. Reduced labor costs will naturally result in increased profit, but this benefit can be used in more strategic ways. Increased labor utilization, once fully realized, can be transferred to more accurate product costing, which can then be directed according to the business strategy of the company. An increased profit margin may, indeed, be the goal. Additional possibilities include an increased competitive pricing advantage leading to increased market share, room in the profit margin for increased options or enhancements, and so on. More accurate product costing practices will make these possibilities available to upper management.

Labor savings are often compounded by overhead allocation methods. Many traditional cost accounting systems allocate overhead on the basis of labor costs. It is crucial that cost accounting understand the impact of labor savings to accurately determine the effect on the total cost structure. As more companies move toward lean manufacturing, the relationship between finance and industrial engineering is becoming more important.

Variance Analysis. Caution should be exercised that theoretical labor savings not be confused with actual labor savings. Engineered labor standards will often result in variances between actual labor and standard labor. This is often because problems that were previously disguised by loose standards are no longer masked. For a more complete discussion on accounting systems see Chaps. 3.3 and 3.6.

Variances are one of the biggest opportunities to result from the implementation of engineered labor standards. They make evident root causes of problems that may not have been obvious prior to implementation of accurate standards. The stigma that negative variances are bad often leads to inaccurate product costing because products are either overcosted to hide the negative variances (often through arbitrary accounting factors) or undercosted by claiming theoretical opportunities before they have been attained. Either situation will hinder the fulfillment of true opportunities. Variances should be recognized as the opportunities that they are.

Variance Accounting. While realizing that these opportunities to fix broken processes exist, actual savings should not be claimed until after the opportunity has been realized. Imagine claiming a 10 percent increase in sales because of a proposal that was submitted. Actual revenue would not be claimed until the contract was rewarded.

Many companies recognize the difference between historical actual (or prior standard and engineered standard costs through the use of budgeted variances. In this manner, historical costs are fully budgeted, but in two pieces. The first component being engineered standard labor costs, the second being the difference between historical actual (or prior standard) and the engineered standard, or budgeted variance. These budgeted variances are often depreciated through the year.

For instance, if historical actual labor cost was $100,000 per period, and engineered standard labor cost is theoretically $50,000 per period, by allowing 10 periods to realize the $50,000 opportunity the labor budget in Fig. 5.7.5 would be typical. This example assumes straight-line depreciation of the budgeted variance. The exact time period over which the opportunity is allowed to be realized and the method for declining the budgeted variance will vary depending on the situation and magnitude of the opportunity.

Systems Interfacing. All engineered standards should be dynamically integrated with the labor reporting system. This will often result in a transfer of standards into a system such as a manufacturing resource planning (MRP) or ERP scheduling system, and should also incorporate any separate cost accounting systems.

In incentive environments, it is also vitally important to integrate payroll systems with the new standards. This system should be checked to ensure that all systems are functioning properly prior to going live with the new system. Prior to implementation, all systems should be checked for compatibility and compliance. Integration might also be required for load and capacity planning systems, scheduling systems, or capital justification packages.

Performance Analysis. The primary problem that will be encountered in managing to engineered labor standards is that some operators will be unable to meet standard production requirements. This will often be due to a lack of training in the standard method and should be easily overcome through retraining (the amount of training required obviously depends on the complexity of the job). Occasionally, a worker will not meet standard due to poor effort. *Poor effort* is defined as one or more of the following: a dispirited attitude, a slowed-down working pace, many false motion and unnecessary activities, “killing time,” poor housekeeping, or lack of interest in the work.

Several steps can be taken to overcome poor effort. First, the situation must be addressed. In a case of poor performance, the supervisor must document any instances of substandard performance. Note the day, time, work center, part number, and number of pieces produced by the operator for every instance where the occurrence of poor performance is noticed. This is the keystone of labor reporting.

If a trend is observed, transfer the operator to another work center, and replace the operator with another, average-skilled worker. Preferably this worker would be one who has the trust of other workers on the floor and is well respected by all parties. Instruct the new operator on the required method per the method description sheet and have the new operator begin to produce parts. Count the number of parts produced to determine the ability of the new operator to meet the required rate. It may take some time for the new operator to achieve standard, depending on the complexity of the method to be learned.

Once standard is being met, discuss the issue with the original operator explaining that others are able to produce parts at the required rate. The first operator should be informed that he or she will be given one more chance on the next shift and that if the required rate is not obtained then appropriate disciplinary action will be taken.

Another difficult issue, especially in a day work environment, is motivation. Supervisors (and industrial engineers, to a lesser extent) must become coaches and motivators in this situation. There are six keys to motivating employees in this situation:

Period	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**
Standard Labor ($1,000 s)	50	50	50	50	50	50	50	50	50	50	50	50
Budgeted Variance	50	45	40	35	30	25	20	15	10	5	0	0
Total Budgeted Labor	100	95	90	85	80	75	70	65	60	55	50	50

FIGURE 5.7.5 Variance depreciation table.

1. Ask for performance. Describe how the job is to be done, explain the expectations of the job, and do not accept less.
2. Extend personal, positive reinforcement. Thank people for performing at or near the standard. Praise them every time they improve further.
3. Build relationships. Do not be afraid to show respect for individuality and trust for intentions.
4. Understand the operator's point of view. Make a habit of listening to people and listen with an open mind.
5. Model what you want. Approach work with a sense of urgency. Show employees through example that the job and the company's success really matter, quality is important, and deadlines are real.
6. Refuse to accept poor performance. Demonstrate that the standards matter by being prepared to tell employees their performance is unacceptable. Sometimes this may require a reprimand.

See Chap. 2.3 for a more detailed discussion on motivating employees. There will also be occurrences where performance exceeds 120 percent performance level. If this trend is noticed, the standard should be audited to ensure that the method on which it is based is being followed. Further information on the auditing procedure is covered in the next section of this chapter.

MAINTENANCE OF ENGINEERED LABOR STANDARDS

Purpose of a Standards Maintenance Program

Methods changes require revisions in labor standards. Some of the changes are readily apparent, in which case the adjustment of standards becomes a routine function. Other methods improvements are much less obvious, including categories such as:

- Combined operations to reduce handling time
- Informal design and development of simple jigs or fixtures developed in the shop
- Modifications to existing jigs or fixtures through informal revisions for easier part insertion or removal
- Workplace layout changes by operators or supervisors
- Manual functions that were external to machine time are changed to internal functions.

Definition of a Standards Maintenance Program

To protect the investment in developing and implementing labor standards, it is imperative that a periodic maintenance program be instituted. Methods improvements are necessary and desirable to reduce costs and stay competitive. It is virtually impossible to update every standard as each method change occurs; therefore, a hurdle rate is used to measure when a change is significant. If the labor standards accuracy is ±5 percent, then a significant change will have occurred when the current method differs from the standard method by more than ±5 percent.

Organization and Resources

In addition to passively adopting reported methods changes, the industrial engineering department should periodically audit the standards on the floor. A good standards audit program will cover a reasonable number of the active standards in a year. Without cooperation from the people involved with the work and a proactive audit program, the standards will steadily deteriorate until they lose credibility and become useless. It is the responsibility of employees to control costs and improve productivity by keeping the standards and methods in line.

Scope and Frequency of Audits

The goal of the periodic audit program should be to review operations with established labor standards every 6 to 24 months. This will fall into four fairly distinct categories of auditing frequency:

1. A certain number of standards will become obsolete within 24 months and be replaced by new standards. This can vary greatly from organization to organization and from industry to industry. A fairly stable industry can expect to see a 20% turn-over while a more dynamic industry might see a 100% turn-over on standards within 24 months. This would represent the Y intercept on the graph shown below.
2. A fairly small number of the remaining standards will represent 20% of the total direct labor hours. This means that a small number of standards will have at least 20% of all direct labor hours reported against them. These standards should be audited every 6 months.
3. Another fairly small number of standards will represent the next 20% of hours. These standards should be audited every 12 months. This means that in aggregate, for a stable company that has a 20% turn-over in 24 months, standards representing 60% of all direct labor hours should be audited within a year.
4. The standards that represent the remaining 40% of direct labor hours should be audited within two years.

This approach is similar to the Pareto approach, and can be represented graphically as in Fig. 5.7.6.

The standards to be audited can be preselected or selected on an availability basis, but should satisfy the established frequency of the audit.

Preselected Audit: advance selection of the jobs you will observe for the audit.

Available Audit: selection will be determined by what the plant is running. This is easier than the preselected audit since there is no long wait for the predetermined job to begin production.

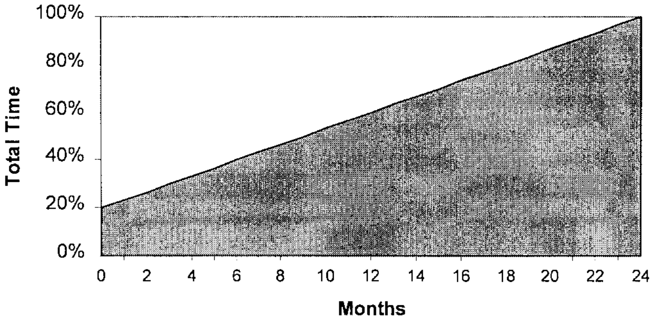

FIGURE 5.7.6 Standards auditing frequency.

Auditing Procedure

Once the list of potential standards is developed, the following steps should be followed to conduct an audit in a company using standard data or time study to set labor standards.

1. Determine the elements or suboperations that account for 80 percent of the standards selected.
2. Observe the methods of these (the 80 percent) elements and compare with the existing elemental analysis. Use the following process to determine the accuracy of each standard.
   - Validate using methods comparison. It is important to note that validation should be consistent with the method of measurement. If a predetermined system was used to develop standards, they were set based on work method. They should be validated in the same way. The majority of validation studies should focus on elements that occur at least once per cycle. It is recommended that both setup and run operations are selected, but not necessarily an equal portion of each, and that operators are selected whose performance is near normal (100 percent) for these studies. Observe the frequencies of the elements that have frequencies of less than 1 and compare with the standard. Resolve any differences and update the frequencies applied in the time standard as required.
   - Observe the operation and record observed methods performed by element. If changes have been made to make the operation more efficient and with equal or better product quality, the analysis should be updated to reflect that method. If changes are observed that make the method less efficient, the industrial engineer should verify that the original method is still feasible and notify the department supervisor to instruct the operator accordingly. Observe feeds and speeds, gauges, process conditions, and times to determine if changes have been made. Check to see if machine or engineering specifications have changed, or if there have been any design changes to the part or product being produced. Verify, through a watch check, the machine/process time—if applicable. If the operator is using substandard methods and/or machine process times, corrective action should be taken.
3. A written summary of the audit should always be prepared by industrial engineering and reviewed with the responsible supervisor and/or production manager. Regular standard audits are a requirement for the maintenance of the labor standard system and should be part of each industrial engineer's weekly duties.

Updating Standards

In those cases where observed manual methods or process times are more efficient than the documented standard methods, it is necessary to analyze the effect of the changes on the standard and to revise the standard in accordance with the policy of the company and union contract.

Implementing Updated Standards

Any changes to existing standard that result due to industrial engineering audits should be communicated first to the supervisor directly responsible for the area. Many union contracts state that no changes are to be made to existing labor standards until the cumulative effect of method changes exceeds a threshold, typically 5 percent. New method sheets should be posted and communicated to the employees in the same manner as they would be during the original implementation. This includes not only communication with employees and operations management, but also constant communication with the finance and costing departments.

Consequences of Not Maintaining Standards

Managers with extensive experience in cost control functions believe that as much as a 40 percent decrease in productivity is possible without a carefully applied systematic control plan. Even with a sound basic plan, there may still be gradual standard erosion. Even qualified supervisors are often unable to detect the possibilities of "creeping" methods change due to the combination of methods effectiveness and work pace.

This will result in rising labor costs (often experienced through escalating incentive earnings, decreased employee productivity, and increased overtime), inaccurate product costing, and the inability to accurately schedule customer orders. Often these changes are gradual and quite frequently the cause of these symptoms is not even recognized. The first place to check is always the labor standards maintenance program.

SUMMARY

The best work measurement and performance management program will not deliver any helpful information to the organizational management until factory management has accepted the concept and bought into the benefits of the program. Commitment to the new standards is essential. Development of a structured approach, gaining management support, and communications are the cornerstones of installing a work measurement and performance management program. Labor standards are an integral part, but nonetheless, only a part of this program. It is important that training be conducted at all levels of the organization to introduce new ideas, measures, and processes developed as part of the new labor standards. The employees should be included in the process and can, as a group, be one of management's strongest supporters.

Changes in methods, equipment, materials, designs, and processes will continue to occur and may not always be apparent. A good labor standard requires that the employees agree that it reflects the production process and provides an accurate measure of the true time the operation takes. A regular assessment of the labor standards through application audits, methods evaluations, and labor reports will keep the work measurement program performing permanently at the level of accuracy for which it was designed.

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BIOGRAPHY

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CHAPTER 5.8

WORK MEASUREMENT IN AUTOMATED PROCESSES

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The main objective of measuring automated processes is to enhance overall productivity. In this chapter, the rationale for measurement is explained, along with common characteristics of automated systems. Examples of work activities that strongly influence the overall productivity of automated systems are outlined, including the importance of employee (human) involvement. Five categories of work measurement techniques are briefly discussed: predetermined time systems, direct observation timing, work sampling, historical data, and judgment estimating. Guidelines for technique selection are provided based on the level of system control. Typical uses of work measurement standards are outlined. Changes in work measurement for automation in the future are identified.

INTRODUCTION

Automated processes today include a wide variety of computerized mechanization. Automation is found in varying degrees throughout manufacturing industries, the service sector, and government. The degree of mechanization may range from very little, for example, one piece of automated equipment in a discrete component manufacturing setting, to a very high level that would be found in a completely automated controlled process plant. Today, automated processes are utilized by companies producing both low and high volumes of output. Automation is found in large corporations and in small companies producing many different kinds of goods and services. *The main objective of measuring automated processes is to enhance overall productivity.*

The principal components of mechanization include a diverse range of computer software and hardware, sensors, machine tools, robots, automated material-handling and positioning equipment, and other mechanized machinery. Most automation designs require modules of intelligent control linked to machinery that performs work tasks. In larger-scale automation, these modules are interfaced to form a total system.

The Need to Measure Automated Processes

If it has been correctly determined that a process should be automated, then a work measurement approach to determine the production output is clearly justified. A false belief, still held by some engineers and managers, is that the more automatic a production system is, the less important it is to measure it or to expend resources or provide motivation or incentives for the operators involved. The simple rationale for this false belief is that human operators have little or no influence on the output of computer-controlled, machine-paced processes. This rationale will almost always lead to low equipment utilization (excessive downtime), poor-quality output, and high system maintenance costs. Often, a combination of these inefficiencies will so adversely impact costs that the predicted economic justification for the automated system is not realized. Experience has shown that, after installation, several automated systems have had higher unit costs than the production processes they replaced. Most of these situations can be avoided with the proper application of work measurement and human motivational techniques.

THE NATURE OF AUTOMATION

Automated systems make it possible to transfer physical and mental work from humans to machines. Properly designed and utilized, they can reduce the unit cost of production. The automated system should also have positive effects on quality, throughput time, and the ability to respond to rapidly changing customer requirements. The level of automation is also influenced by material and energy utilization, operator safety and health considerations, availability of capital and qualified human resources, and the estimated life of the products or services being produced.

Several methods may be used to evaluate possible automation opportunities and to aid in making the final decision. Most of these methods include a cost-benefit analysis comparing the proposed automated system with the existing or previous production technology utilized. The cost part of the analysis should consider costs of labor, material, overhead, and all capital and other implementation costs. These calculations can be assisted with an engineering economy approach and work measurement analysis.

In addition to the conventional cost analysis, proposed automation system evaluation should include intangibles, or opportunity costs—for example, loss of unproduced units or profits or loss of market share because of system downtime and failure to satisfy customer requirements. Remember, the major objective of automated processes measurement is to realize the maximum potential output of the total system.

Benefits and Concerns

Many factors justify automation in a given work situation. The more common factors include the need to increase production output (market expansion), reduce labor costs, and increase profits. Example benefits that usually have a positive cost impact include reduced throughput time, increased use of standard parts and tooling, and greater utilization of equipment and physical plant.

Major limitations and concerns associated with automation include large capital investment, rapidly changing technology, and personnel problems. The large capital investment has to be amortized into the product or service cost structure. Most automation modules or systems are continuously being improved, and with each design they become more cost effective. Consequently, there is always a risk of obsolescence. Perhaps the most difficult aspect of automation limitations and concerns is personnel problems. The most common human issues associated with automation implementation include resistance to change and training. Developing attitudes to accept automation and training is necessary for all levels of personnel: hourly, supervision, and management.

Common Characteristics

The determination of how to measure automated processes requires an understanding of the system and its impact on specific business needs. The following paragraphs summarize common characteristics of automated modules and systems.

In addition to the aforementioned factors that justify automation, reasons for mechanization include improved quality, greater production uniformity, and safety and health considerations. Facility construction costs place an increasing emphasis on better space utilization by consolidating individual machines or manual operations into an automated system. Human behavioral and safety considerations include automating those elements that are highly repetitive (to prevent cumulative trauma injury) and have a high output volume.

Capital investment is usually very high in comparison with manual or partially mechanized systems. In fact, costs can range from tens of thousands of dollars per worker to a multimillion-dollar installation that is monitored, managed, and serviced by a small work group.

Variability in production is inversely influenced by the number of stand-alone production units. When many common individual units are producing, variability tends to be offset from one unit to another. Thus a certain level of production can be closely predicted and relied upon. Conversely, a single but larger production system is either running or on downtime; it's either on or off. When on, it may or may not be producing 100 percent good output, but when off, the system produces zero.

Probability of failure or downtime is much greater in a single, highly complex system. For example, if a group of single machines have a 95 percent probability of being in run mode, then 95 percent of a number of those machines will likely be producing. If a single, complex system has several interdependent modules arranged in series, each with a 95 percent probability of running, the overall probability of run time is the product of the independent probabilities. Thus a four-module system would have a probability of running during only 81.5 percent of the shift time.

Investment justification usually requires a high degree of utilization. Typically, this is a two- or three-shift operation, sometimes for seven days a week. Where overtime formerly could compensate for production breakdowns on a one- or two-shift operation, the new system compresses all variability into one unit running around the clock, and time lost is much more difficult or impossible to replace. Fluctuating production schedules may compound the problem of lost production time and capacity, even resulting in lost customer sales. These facts often necessitate backup equipment, requiring even higher capital investment.

Labor content in highly mechanized processes is low relative to depreciation or amortization costs, which continue even during a shutdown. Consequently, measurement must focus on system uptime, not just on individual workers.

Maintenance support is critical for any automated process. The failure of a single component (even minor) can cause shutdown of the module or entire system. Maintenance costs are higher in automated systems than in less mechanized operations because of the need for higher technical skills, longer shutdowns during production runs, and around-the-clock troubleshooting availability. If the maintenance service reports to someone other than the production manager, this will likely be a source of functional and jurisdictional difficulties. The best management approach is to include maintenance personnel in the automated module or system work group.

The Human Component

Knowledge and human know-how is vital to the successful operation of any automated module or system. Therefore the work environment must be structured to ensure employee involvement and team building. Examples of work activities that strongly influence the overall productivity of the automated module or system include the following:

1. Monitoring and control to preserve the level of quality engineered into the product or service.
2. Maintaining raw material supply, inventory, and waste disposal conditions to extend run time.
3. Exercising online preventive maintenance to avoid downtime through minor servicing and adjustments that do not require shutdowns.

4. Troubleshooting as quickly as possible whenever breakdowns occur to minimize downtime. This requires maximum knowledge and communication among operators and maintenance or other service people.
5. Changing products or machine setups as quickly as possible to avoid excessive downtime. This requires maximum communication and cooperation among members of a work group or among several groups and rendering effective assistance to coworkers or other specialized service staff during scheduled maintenance periods.

EMPLOYEE INVOLVEMENT

This concept is not a new idea. For example, in the 1930s Joseph W. Scanlon developed the Scanlon plan. Its major purpose was to measure overall productivity improvement and distribute a share of any gains to the employees. In addition, the plan included labor/management committees to effect improvements throughout the manufacturing operation. Beginning in the 1960s and continuing today, behavioral scientists have showed the benefits of democratic management and worker participation. These benefits have been further reinforced by Japanese management practices and European work groups (e.g., Volvo in Sweden). The outgrowth of this has yielded self-managing (involvement) work teams throughout manufacturing and the service sector.

Types of Programs

Involvement teams have emerged in the United States in many forms and are a vital part of successful automation. Several distinct forms range from small problem-solving groups of only hourly workers to well-organized, self-managed work teams comprising all skills necessary to run the automated system. The work teams have complete responsibility and decision-making authority for their part of the automated system. Experience has shown that increased involvement leads to more effective decisions in most complex situations.

Quality Circles. This involvement group usually consists of 8 to 10 members who do similar work and agree to meet on a regular basis to discuss work and quality problems. The group analyzes causes of problems and recommends solutions to management. Group members may also take action to assist implementation of recommended solutions. Quality circle activities usually enhance motivation and the overall quality of work life.

The quality circle leader is commonly a supervisor of all or several of the group members. In addition, each circle has a facilitator who is responsible for training the members and the leader. The facilitator forms a link between each circle and the rest of the organization, and he or she may also take an active role in the measurement and evaluation of improvements.

Work Teams. This involvement group usually consists of all the workers necessary to totally manage and operate an automated module or system. They are self-managed and are given considerable decision-making responsibility over their work area. Unlike in quality circles, the team is assigned full-time to a specific work area.

Work measurement is essential to properly determine staffing levels by skill type for any self-managed group.

MEASUREMENT TECHNIQUES FOR AUTOMATION

Measuring automated processes is necessary to determine the correct human support staffing requirements and to establish a basis on which to evaluate total output performance. The measurement system should provide performance data on the automated process for feedback to the self-managed work group and higher management. The system should be structured and used in a way that permits the application of incentives and enhances motivation. In addition, it should be a dynamic process of information generation whose primary goal is to establish direction for continuing improvement in output productivity, quality, lower costs, improved worker safety and health, and better products and services for timely customer delivery.

The following five categories of work measurement techniques will be briefly discussed:

1. Predetermined time systems
2. Direct observation timing with performance rating (stopwatch time study)
3. Work sampling
4. Historical data (includes accounting records and self-logging)
5. Judgment estimating

The first three are considered engineered work measurement techniques. The last two—historical data and judgment estimating—are often used to approximate standard time values. However, these techniques offer decreased accuracy and little in the way of underlying theory or standardized procedures and consequently are not considered good engineered work measurement practices. An additional approach—standard data and mathematical modeling—is also useful in the establishment of work standards. The engineer must be aware of the accuracy required for a given production standard or other work measurement application when using any of these techniques.

To varying degrees, all of the foregoing techniques may be used for the measurement of automated work, depending primarily on accuracy requirements, but also considering availability of human resources, time to determine the production standard, and management objectives. It is important to know the strengths and limitations of each technique. This is useful in technique selection when evaluating the cost of establishing production standards versus the cost of having inaccurate or no production standards.

Predetermined Time Systems

By definition, a *predetermined time system* is "an organized body of information, procedures, techniques, and motion times employed in the study and evaluation of manual work elements. The system is expressed in terms of the motions used, their general and specific nature, the conditions under which they occur, and their previously determined performance times" (ANSI Standard Z94.12).

Predetermined time systems can be classified as generic, functional, or application-specific. *Generic systems* are not restricted in any way and are widely used by many types of organizations. *Functional systems* are adapted for a specific activity type, such as machining, clerical, or microassembly. *Application-specific systems* are designed for the operational needs of a particular industry or organization, like aircraft engines, banking, health care, or individual companies.

Numerous predetermined time systems have been developed over the years. Examples include methods time measurement (MTM), work factor, motion time study (MTS), modular arrangement of predetermined time standards (MODAPTS), master standard data (MSD), robot time and motion (RTM), and Maynard Operation Sequence Technique (MOST®). While each has certain features, most of the systems have similarities in their structure. Because of its wide usage, versions of the MTM system will be discussed here for application to automated processes.

Several predetermined time systems are based on a fundamental or detail structure. These are considered first-level generic systems. Higher-level systems are those developed with elements that include multimotions or combinations. For MTM, the fundamental level is MTM-1. Higher-level generic variations include the following:

- MTM-2: Based on MTM-1 with about twice the speed of analysis, but less accuracy than MTM-1.
- MTM-GPD (general-purpose data): Based on MTM-1 to group common motion patterns. Less analysis time and lower accuracy than MTM-1.
- MTM-3: Based on MTM-1 with about seven times the speed of analysis and less accuracy than MTM-1. Ideal for long-cycle work.

Examples of MTM functional variations include the following:

- MTM-M: For subminiature assembly completed in a microscopic field.
- MTM-C: Clerical activities.
- MTM-V: Machine tool use data system.

Other MTM outgrowths include micromatic methods and measurement (4M), and Maynard Operation Sequence Technique (MOST). A computerized work measurement system developed at Westinghouse, 4M retains MTM-1 accuracy and element description while providing a faster speed of analysis. The MOST system utilized a larger number of motions in elements than MTM-2 and therefore requires less time for analysis, especially in its computerized version. Both 4M and MOST represent excellent examples of the positive effects of computerizing a predetermined time system. MOST can be used for all types of cycle time variations.

Stopwatch Time Study

The Industrial Engineering Terminology Standard (ANSI Z94.12) defines *time study* as “a work measurement technique consisting of careful time measurement of the task with a time measuring instrument, adjusted for any observed variance from normal effort or pace and to allow adequate time for such items as foreign elements, unavoidable or machine delays, rest to overcome fatigue, and personal needs. Learning or process effects may also be considered. If the task is of sufficient length, it is normally broken down into short, relatively homogeneous work elements, each of which is treated separately as well as in combination with the rest.” Stopwatch time study is useful for determining more frequent work activities associated with the automated process.

Work Sampling

The Industrial Engineering Terminology Standard (ANSI Z 94.12) defines *work sampling* as “an application of random sampling techniques to the study of work activities so that the proportions of time devoted to different elements of work can be estimated with a given degree of statistical validity.” The technique can be applied to humans, machines, or any observable state or condition of an operation. The underlying assumption of work sampling is that the sampling percentage of any observed state of nature estimates the actual time spent in that condition.

Work sampling with performance rating can be used in manufacturing, service organizations, and government for cost-effective work measurement. The technique is particularly useful for the following:

- Determining allowances
- Determining machine and equipment and/or facility utilization
- Production standards for indirect and support personnel
- Production standards for long-cycle, higher-production-quantity operations
- Development of standard data

Work sampling can be used for determining production standards for automated processes. For limited production runs, lower accuracy and greater error limits are designed into the study. This reduces the number of observations (and time) required to complete the study. Common guidelines for the confidence interval and error limits are 95 percent and plus or minus 5 percent, respectively. However, in all work sampling applications, the engineer must use judgment about the activity or state being observed and the overall accuracy requirements to determine the correct confidence interval and error limits.

Historical Data

While not an engineered work measurement technique, historical data is very cost effective for the development of production standards. Historical data are a special, less accurate form of standard data. Times are developed for work activities from previous actual recorded times (job accounting records). Task times may also be developed by support workers using self-logging times for activities. These time data can be statistically averaged and evaluated.

Historical data–based production standards can be used in any work activity for automated operations. The time and cost to develop standards with this technique are minimal compared with other work measurement techniques. The obvious limitation is accuracy of the resulting production standards.

Judgment Estimating

As with historical data, judgment estimating is not an engineered work measurement technique. It is the least accurate, but it also requires the least amount of time to establish production standards. Many practitioners dismiss judgment estimating because of its accuracy limitations. Experience has shown that production standards established with judgment deviate from the true standard by at least 50 percent. There is, however, a methodology to improve judgment estimating.

The recommended five-step procedure for developing a judgment estimate is as follows:

1. Subdivide the total job into major activities (tasks). This helps define what has to be done and enhances the estimating process.
2. Clearly understand the physical setting of each activity (task) to be performed (e.g., workplace, tools, equipment to be used and the job environment).
3. Think in terms of producing one unit of output, that is, a production cycle following any setup or get-ready activities. As with all work measurement production standard setting, setup or get-ready activities should be estimated independently.
4. Assume the task will be performed by an average skilled and trained operator.
5. Complete the task time estimate. This can best be accomplished with a process commonly used in critical path scheduling models such as program evaluation and review technique (PERT). These models commonly use judgment estimating to determine the time values for each activity (task) identified within the network. In place of estimating only one value for the total task, three estimates are completed: an optimistic time, a pessimistic time, and a most likely time. The optimistic and pessimistic time estimates require the engineer to mentally establish minimum and maximum time boundaries considering the major factors that could cause variation in task completion. The task time estimate conforms to the beta distribution and can be calculated with the following equations:

$$T_e = \frac{t_o + 4t_m + t_p}{6}$$

where T_e = mean of the beta distribution, the mean time estimate for the task
t_o = optimistic time estimate
t_m = most likely time estimate
t_p = pessimistic time estimate

and for the standard deviation,

$$\sigma = \left(\frac{t_p - t_o}{6}\right)^2$$

Measurement Technique Selection

The work activities of humans in automated processes vary depending on the level of system control. Karwowski and Ward (1989) have defined four levels of control: manual, semiautomatic, supervisory, and cognitive, as depicted in Fig. 5.8.1.

The manual system (level 1) shows the operator controlling and monitoring output of the production system. In this nonautomated case, the work measurement technique selection would be more conventional and would depend on quantity produced, length of production run, and type of job function.

Level 2 depicts system control commonly found in modular automation such as a single NC machine tool. In this case, the operator(s) would be performing job functions such as load, unload, monitoring, setup, and maintenance. Therefore, work measurement selection should generally follow the guidelines for low-quantity work.

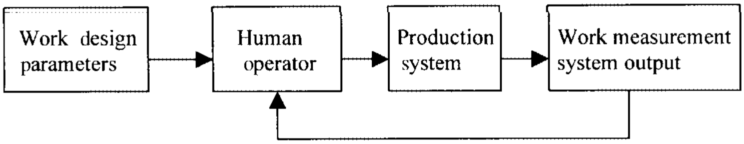
The supervisory and cognitive systems (levels 3 and 4) are typical of a flexible manufacturing cell (level 3) or a fully automated process plant (level 4) that require human interface only with the controller. The controller then instructs and receives feedback from the production system through computer control and various system-state sensors. The primary activities of the work group include monitoring of the process and quality, maintaining supply, maintenance and troubleshooting, setup and changeover, and other support functions. While all work measurement techniques may have some utility, work sampling and predetermined time systems have the most applicability for automated processes.

USE OF WORK MEASUREMENT DATA

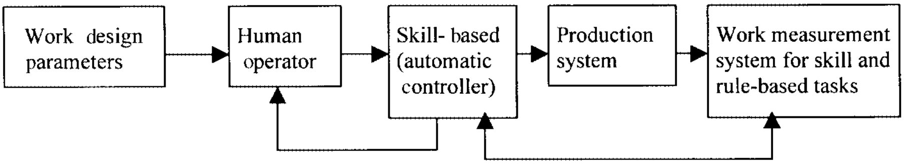
Measurement of automated processes will realize standards that are useful for staffing determination and control, production output, work-group building, and incentive pay determination. In addition, a measurement program is helpful for the following:

1. Evaluating personal, fatigue, and delay allowances
2. Debugging the new system for improved performance
3. Evaluating equipment changeover
4. Designing preventive maintenance procedures and schedules
5. Redesigning marginal components of the system
6. Developing job descriptions and training procedures
7. Enhancing cooperation among the work group, including operators, maintenance, and management
8. Determining interference patterns within the work group and/or between the human equipment interfaces
9. Estimating labor and equipment capacity and scheduling capabilities
10. Evaluating and measuring indirect and support personnel

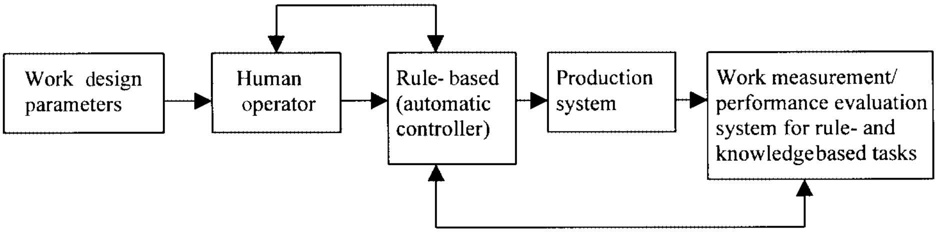
Level 1. Manual system control


Work design parameters
Human operator
Production system
Work measurement system output

Level 2. Semiautomatic system control


Work design parameters
Human operator
Skill- based (automatic controller)
Production system
Work measurement system for skill and rule-based tasks

Level 3. Supervisory system control


Work design parameters
Human operator
Rule- based (automatic controller)
Production system
Work measurement/ performance evaluation system for rule- and knowledgebased tasks

Level 4. Cognitive system control

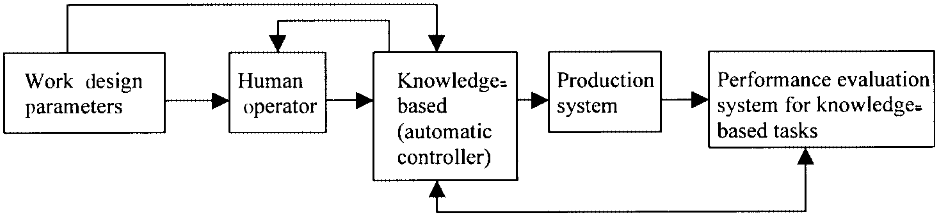

Work design parameters
Human operator
Knowledge-based (automatic controller)
Production system
Performance evaluation system for knowledge-based tasks

FIGURE 5.8.1 Work measurement for different levels of computer-aided automation. *(Adapted from W. Kawawski and T. L. Ward, "Work Design and Measurement: Critical Issues for Advanced Manufacturing," Proceedings, International Industrial Engineering Conference, Toronto, 1989, p. 514, Copyright Dr. W. Karwowski, Department of Mechanical Engineering, Tampere University of Technology, Tampere, Finland.)*

11. Improving methods and procedures
12. Determining whether the automated system should be provided with a manual or module insert replacement for backup during extended periods of breakdown
13. Providing data to compare the total cost-effectiveness between various levels of operation or automation to produce a given output

THE FUTURE

As computer and sensor technology develop and combine to realize lower-cost intelligent systems, automation applications will continue to increase in the years ahead. Clearly, the future holds higher levels of automation for both manufacturing and the service sector. The trend in automated manufacturing is the ability to process different components, models, or families of assembled items on the same system and in very small lot sizes as may be required by the customer. The service sector is moving toward completing information or service transactions with less (or no) human interaction. It is important to note, however, that even the most automated production process will require humans for maintenance and other support functions. Consequently, the need for work measurement in automated processes will still exist, but there will be changes. These changes may be briefly summarized as follows:

Stopwatch time study. The requirement to conduct direct observation timing and the associated rating or leveling of human performance will decrease because of the increased machine- and computer-controlled processing cycles. Most cycle times will be automatically determined from clocks and calendars within the control device.

Allowances. While the determination of personal, fatigue, and delay allowances will be accomplished as in the past (work sampling), there will be changes as automation levels increase. In general, physical fatigue will decrease and mental fatigue will increase. Unavoidable delays in highly automated processes will be different from those in traditional manufacturing plants or service operations.

Work sampling. The use of this proven work measurement technique will increase as automation continues to evolve. The practice of work sampling will be simplified because of the ability to electronically monitor and record the activity state of many elements of the automated system.

Predetermined time systems. This work measurement technique will still be used in the traditional form primarily for indirect and support personnel. Computerized synthetic time systems will be developed to improve application to the activities of knowledge workers. Specialized predetermined time systems, such as RTM, will become more useful for future automation applications.

Standard data. For estimating and planning purposes, standard data will probably be developed for major segments of the automated system in contrast to small elements of an individual processing cycle. With major segments of processing times included in a computerized database, cost comparisons could be more easily made for alternative methods of production.

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BIOGRAPHY

Richard L. Shell, Ph.D., P.E., is Professor of Industrial Engineering in the College of Engineering and Professor of Environmental Health in the College of Medicine at the University of Cincinnati. His specialization areas include ergonomics/safety engineering, human performance, incentives/motivation, and manufacturing. Before joining the UC faculty, Shell's business experience included engineering and management positions with Bourns Corporation, Ampex Corporation, and IBM. He received the Institute of Industrial Engineers Fellow Award in 1988, and was elected a Fellow of the Society of Manufacturing Engineers in 1995. His most recent book, *Time Based Manufacturing,* was coauthored with Joe Bockerstette and copublished by Industrial Engineering and Management Press (Norcross/Atlanta) and Mc-Graw Hill (New York), 1993.

Source: MAYNARD'S INDUSTRIAL ENGINEERING HANDBOOK

CHAPTER 5.9

CASE STUDY: AUTOMATED STANDARD SETTING FOR CASTING AND CAST FINISHING OPERATIONS

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The conventional methods used to establish accurate labor standards often require considerable input of industrial engineering time and effort. Commonly, it takes anywhere from several minutes to several hours to determine one operation standard. By using front-end expert system technology it is possible to substantially reduce this time while improving the accuracy and consistency of the standards. This technology allows the applicator to automatically set standards by answering only a few part-characteristic questions. This case study describes how AutoMOST® logic trees combined with standard data and part-characteristic tables were used to simplify standard setting for highly variable parts in casting and cast-finishing operations.

BACKGROUND

The Pfaltzgraff Company, a leading manufacturer of premier stoneware and fine china, asked H. B. Maynard and Co., Inc., for assistance in developing engineered standards for its West York and Bendersville, Pennsylvania, facilities. Pfaltzgraff manufactures and distributes dishes and accessories, including plates, bowls, pitchers, gravy boats, and lamps. Pfaltzgraff also provides matching accessories for its dinnerware lines (napkin holders, wallpaper border, tea towels, etc.). The casting and cast-finishing departments produce approximately 400 different types and hundreds of different styles of items and accessories.

The project started with top-down analysis to determine the suboperations (standard data elements) needed to cover the casting and cast-finishing areas. *Top-down analysis* is a data structuring technique that identifies all necessary elements and minimizes duplication of the measured blocks of work. The intent was to use existing data where applicable and develop new data as required to provide statistically accurate standard data coverage for approximately 45 employees in West York and 11 in Bendersville. The suboperations would also be validated for existing conditions in both plants.

The next step was to develop expert system logic to set operation standards for casting and cast finishing. AutoMOST is a knowledge-based expert system that allows an end user to answer questions while automatically adding elements of work (suboperations) to the time standard. Therefore, as the user answers simple questions about the part, AutoMOST is adding suboperations to the operation creating the time standard. This technique greatly reduces the time required to set standards. With the many types and styles of parts at Pfaltzgraff, an expert system approach provided a reasonable solution.

Data and logic would be representative of all parts based on those running during the study period. The Pfaltzgraff Company provided two industrial engineers to work with Maynard. The industrial engineers observed and studied process times, collected frequency data, and compiled part-specific data for inclusion into the AutoMOST logic trees as they were being developed. Logic and data were then tested and accuracy validated with test standards in both plants. This work was completed in 18 days.

CASTING OPERATIONS

All casting is completed using the same operations:

1. *Pouring*

Liquid cast, or *slip,* is poured into the molds.

Process time for the molds to set.

2. *Dumping*

Molds are turned over to let the excess slip drain.

3. *Sparing*

A cutting instrument is used to trim excess (called *spare*) from around the openings in the mold.

Operator uses fingers or wet sponge to smooth around openings of mold (*felting*).

4. *Stripping*

Molds are broken apart and the semiwet items asided to a board.

Molds are cleaned and reassembled.

Board of items is sent to cast-finishing department.

A skeleton AutoMOST tree for the casting operations is shown in Fig. 5.9.1.

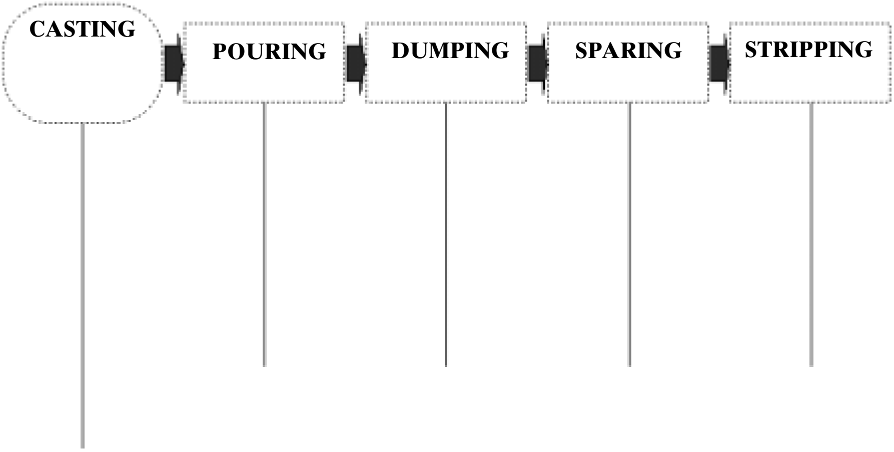


FIGURE 5.9.1 Casting AutoMOST logic tree skeleton.

CASE STUDY: AUTOMATED STANDARD SETTING FOR CASTING AND CAST FINISHING OPERATIONS

Top-Down Analysis

The major task for the team in the first week of the project was to begin the top-down analysis by developing a categorized element list. Following the first step in Maynard's top-down technique, the team decided there would be one "top" that included all casting and cast-finishing operations. After approximately three hours, the analysts had developed a list of roughly 30 elements (suboperations) that were believed to cover all the work in the casting and cast-finishing departments at both plants. The team brainstormed to create the major activity categories that broadly described the type of work for each element: setup, pouring, dumping, stripping, drill/ream/punch, cut/spare/trim, surface treat, decorate, inspect, and miscellaneous. Each element or suboperation would be classified and filed into the database with an appropriate activity. This would allow quick and easy retrieval of the suboperations. Once each element was classified under an appropriate category, the team began the next step in the top-down approach: categorizing each element as *constant* (*C*) or *variable* (*V*) (see Table 5.9.1). Constant elements occur the same way every time; variable elements do not.

Early in the top-down analysis, the team began to discuss the application approach. How would a user want to set a standard? Automated or manually? What would a casting and cast-finishing standard (operation) look like in the end? What information was available? How complicated would it be for someone with limited process knowledge to set a casting or cast-finishing standard? Answers to these questions would affect not only the data development but also the end-user expert system logic. Therefore, it was important to answer these questions early in the project.

After carefully studying the processes used in both casting and cast finishing in each plant, it was evident that the team should tie as much information as possible to the item being made. For instance, process times were available for the pouring of every piece. These times obviously depend on the piece being made. It takes longer to pour the wet clay, or *slip,* for a ball lamp than for a pedestal mug. The design of the piece also determines the mold complexity. Some items have molds consisting of only two pieces; some molds have a pill (see Fig. 5.9.2), which is another piece that needs to be prepared, assembled, disassembled, and cleaned; some molds have four pieces.

With so many of the part characteristics driving the work required, the team decided to create a table of key part characteristics. This table would be read by an AutoMOST tree and used to pick the appropriate suboperations. Most important, the thought process of the work measurement analyst would be greatly simplified because he or she would merely need to identify the item being made. Without a front-end expert system, this approach would not be ideal, since the end user would need to keep referring to the part-characteristic tables. By using AutoMOST, the lookup table adds no extra time to the end user's work, and a higher level of accuracy is attained. This high level of accuracy comes from a reduction in applicator error in setting the standards and in the reduction of averaging times, a technique commonly used when many similar but unique parts are involved. Achieving a high level of accuracy was important to Pfaltzgraff since the standards would be used for wage incentive purposes.

The first step in creating the key characteristics table was to get a list of all items cast. Next, this list was entered into a spreadsheet that would be expanded to include all key characteristics for each part. This key characteristics table would be vital to both data and logic development. Table 5.9.2 shows the casting key part-characteristics table.

Data Collection and Suboperation Development

Pouring. Data collection began in the first activity of the casting operation: *pouring.* The measured work in pouring would consist of a constant suboperation for the initial setup and a process time for the pouring. This process time would not be stored as a suboperation but would be put in the operation as a separate line item called a *machine operation* (MO). The software used to house the time standards (operations) was Maynard's MOST Data Manager®. In MOST Data

TABLE 5.9.1 Top-Down Analysis

Activity category	Constant/Variable	Element	Department	Variations
POUR	V	Process time for pouring	Casting	Size, restrictions to opening
DUMP	V	Dump into cart	Casting	
DUMP	C	Extra turn for chimed molds	Casting	
DUMP	C	Turn mold right-side-up	Casting	
DUMP	V	Drain lamp	Casting	
STRIP	C	Remove top spare	Casting	
STRIP	V	Open mold, aside piece	Casting	
DRILL/REAM/PUNCH	V	Ream hole	Casting	Drill, hand bit with guide; hand bit w/o guide
DRILL/REAM/PUNCH	V	Notch lid	Casting	Tool, hand
DRILL/REAM/PUNCH	C	Punch piggy-bank hole	Casting	
DRILL/REAM/PUNCH	C	Re-ream salt/pepper shakers	Cast-Finishing	
CUT/SPARE/TRIM	V	Cut around top of mold with knife	Casting	
CUT/SPARE/TRIM	C	Additional sparing for pieces with spout	Casting	
CUT/SPARE/TRIM	V	Trim piece	Cast-Finishing	Size, top, inside/outside handle, sponge
SURFACE TREAT	V	Scrape top of mold	Casting	
SURFACE TREAT	V	Smooth with fingers	Casting	
SURFACE TREAT	V	Smooth with flannel (felting)	Casting	
SURFACE TREAT	C	General cleaning of mold after stripping	Casting	
SURFACE TREAT	C	Additional cleaning for pilled molds	Casting	
SURFACE TREAT	C	Sponge with dowel rod sponge	Casting	
SURFACE TREAT	V	Wet-finish top	Casting	
SURFACE TREAT	V	Blowout with airhose	Cast-Finishing	
SURFACE TREAT	V	Stone foot	Cast-Finishing	
SURFACE TREAT	V	Sponge piece (seams and complete)	Cast-Finishing	Function of lineal inches
SURFACE TREAT	V	Flush piece with foot pedal	Cast-Finishing	Size, single/double flusher
SURFACE TREAT	C	Re-sponge lip	Cast-Finishing	
SETUP	C	Setup for pouring (nozzle to hose, etc.)	Casting	
SETUP	C	Lock/unlock bench lock	Casting	
SETUP	V	Re-assemble molds for next pour	Casting	
SETUP	V	Move full boards	Casting	West York vs. Bendersville (methods)
SETUP	V	Setup empty boards	Casting	West York vs. Bendersville (methods)
SETUP	V	Load/unload part to bench/workspace	Cast-Finishing	
DECORATE	V	Stamp	Cast-Finishing	Size
DECORATE	V	Band	Cast-Finishing	Size
DECORATE	V	Stamp and band	Cast-Finishing	Size
INSPECT	C	Gauge salt & pepper shakers	Cast-Finishing	
MISCELLANEOUS	C	Walk between rows for pouring	Casting	
MISCELLANEOUS	C	Shift empty boards	Cast-Finishing	
MISCELLANEOUS	C	Aside foam, etc.	Cast-Finishing	

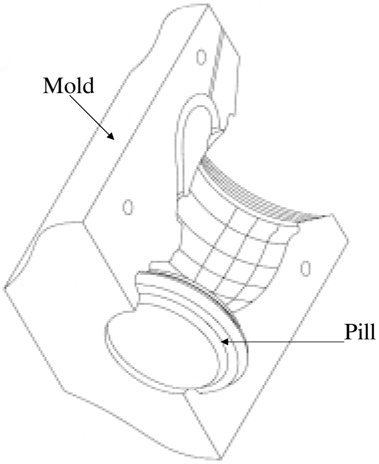


FIGURE 5.9.2 Drawing of mold with pill.

Manager, an MO is used when it is desirable to have the system keep track of the total process time in a standard and, if desired, when a different allowance is to be applied to the process times (MOs). Again, this process time would come directly from Table 5.9.2 under the column called *Pour time* for the respective item. (Figure 5.9.7 shows a sample casting operation.) Notice that the setting up of the molds for a particular batch was not measured, as this is an indirect labor function. Therefore, the measurement starts with the operator preparing the hose and scoop and continues with the pouring and cleanup of the necessary equipment. The initial setup and cleanup of the hose and scoop used in pouring was identified as a constant element and was therefore put into one combined suboperation. The next step was to determine the frequency of this suboperation. To calculate the frequency, the team's research revealed that, on average, there were 650 pieces produced in the casting department within an 8-hour shift. This frequency (2/650) was applied to the suboperation at the operation level.

Dumping. Next, the team moved into the second major activity in the casting operation: *dumping.* In this process, the operator, after a cure time, lifts and turns each mold to dump the excess slip into the slip cart and subsequently returns the mold to the bench. The previous work measurement technique used at Pfaltzgraff allotted a weight allowance to account for differences in the mold weights. Its current system, MOST® (Maynard Operation Sequence Technique), does not allow for a weight allowance in moving items but instead focuses on the differences in the work involved. For example, heavier molds are more difficult for the operator to control and cause more difficulty and care in placement. Also, moving heavier molds takes more operator steps. MOST accounts for these differences in its *gain control, placement,* and *action distance* parameters, and therefore no weight allowance is necessary [1].

Since dumping the molds was identified as a variable element, R_t testing was the next procedure. R_t testing is the process used in the top-down technique to statistically refine elements. Using the allowed deviation formula results in the fewest possible suboperations necessary to maintain the required level of accuracy [2]. Suboperations for the simplest and most difficult cases of dumping a mold were measured using MOST. The R_t analysis showed that for the variations in dumping a mold, two *slots* (suboperations) were required (see Fig. 5.9.3). This technique is sometimes referred to as *slotting.*

Next, the analysts had to determine which molds required the first suboperation, or slot, and which required the second. When considering the simplest and most difficult cases of a variable element, it is likely that only one or two characteristics (e.g., the size of the part, weight, material, tolerances, number of fasteners) are responsible for making one more difficult than another [3]. It was quickly determined that the key variable was the amount of slip within the mold, which in turn was based on the volume of the item being produced. The hypothesis at this point was that the more slip in the mold, the more time it took an operator to dump the mold. To test this hypothesis, linear regression analysis was conducted on slip weight versus pour time. Thirty-five samples were taken on different items and used in the regression analysis. The regression indicated a high correlation between slip weight and pour time—a correlation coefficient of 0.929. This is acceptable for this number of samples with degrees of freedom equal to 31 [4]. Figure 5.9.4 shows the results of the regression analysis.

With this information, it was now necessary to determine the slip weight cutoff for the first slot. Samples determined that if the slip weight of a particular item went over 1.81 kg (4.0 lb), it fell into the second slot for dumping (133–158 TMU) [5]. The reason is that with slip weights

TABLE 5.9.2 Casting Key Part-Characteristics Table

Item	# Pieces	# Holes	Mold top	Pill	Spout	Dump	Chime
BALL LAMP	1	0	TOP	NOPILL	NOSPOUT	DRAIN	NOCHIME
BATTER BOWL	1	0	NOTOP	PILL	NOSPOUT	DUMP	NOCHIME
BEAN POT	1	0	TOP	PILL	NOSPOUT	DUMP	CHIME
BEAR BELL 2	2	1	NOTOP	NOPILL	NOSPOUT	DUMP	NOCHIME
BEV SERVR COVER 2	2	0	NOTOP	NOPILL	NOSPOUT	DUMP	NOCHIME
BEV SERVR COVER 1	1	0	NOTOP	NOPILL	NOSPOUT	DUMP	NOCHIME
BEVERAGE SERVER	1	0	TOP	PILL	SPOUT	DUMP	CHIME
CANDLESTICK 1	1	0	CSHALF	PILL	NOSPOUT	DUMP	NOCHIME
CANDLESTICK 2	2	0	CSHALF	PILL	NOSPOUT	DUMP	NOCHIME
CREAMER (WITH TOP)	1	0	TOP	PILL	NOSPOUT	DUMP	NOCHIME
CREAMER (WITHOUT TOP)	1	0	NOTOP	PILL	NOSPOUT	DUMP	NOCHIME
CYLINDER LAMP	1	0	NOTOP	NOPILL	NOSPOUT	DRAIN	NOCHIME
DISNEY UTENSIL CRK	1	0	NOTOP	PILL	NOSPOUT	DUMP	NOCHIME
EMB. UTENSIL CROCK	1	0	NOTOP	PILL	NOSPOUT	DUMP	NOCHIME
GINGER LAMP	1	0	NOTOP	NOPILL	NOSPOUT	DRAIN	NOCHIME
GRAVY BOAT (WITH TOP, NO C)	1	0	TOP	PILL	NOSPOUT	DUMP	NOCHIME
GRAVY BOAT (WITH TOP, CB)	1	0	TOP	PILL	NOSPOUT	DUMP	NOCHIME
GRAVY BOAT (NO TOP, NO CB)	1	0	NOTOP	PILL	NOSPOUT	DUMP	NOCHIME
GRAVY BOAT (NO TOP, CB)	1	0	NOTOP	PILL	NOSPOUT	DUMP	NOCHIME
JAM POT COVER HAND	2	0	NOTOP	NOPILL	NOSPOUT	DUMP	NOCHIME
JAM POT COVER MACHINE	2	0	NOTOP	NOPILL	NOSPOUT	DUMP	NOCHIME
LADLE	1	0	NOTOP	NOPILL	NOSPOUT	NODUM	NOCHIME
LOTION BOTTLE 2	2	0	TOP	PILL	NOSPOUT	DUMP	NOCHIME
LOTION BOTTLE TOP 2	2	0	NOTOP	NOPILL	NOSPOUT	DUMP	NOCHIME
MAIL BASKET	1	0	NOTOP	PILL	NOSPOUT	DUMP	NOCHIME
MILK BOTTLE	1	0	NOTOP	PILL	NOSPOUT	DUMP	NOCHIME
MINI BATTER BOWL	1	0	NOTOP	PILL	NOSPOUT	DUMP	NOCHIME
ONION SOUP	1	0	NOTOP	PILL	NOSPOUT	DUMP	NOCHIME
PEDESTAL MUG	1	0	NOTOP	PILL	NOSPOUT	DUMP	NOCHIME
PIGGY BANK	1	0	NOTOP	NOPILL	NOSPOUT	DUMP	NOCHIME
PITCHER (1.75 QT.)	1	0	NOTOP	PILL	NOSPOUT	DUMP	NOCHIME
PITCHER (1 QT.)	1	0	NOTOP	PILL	NOSPOUT	DUMP	NOCHIME
SALT/PEPPER 2 (3–4 HOLES)	2	3:4	TOP	NOPILL	NOSPOUT	DUMP	NOCHIME
SALT/PEPPER 2 (6 HOLES)	2	6	TOP	NOPILL	NOSPOUT	DUMP	NOCHIME
SOUP TUREEN	1	0	TOP	PILL	NOSPOUT	DUMP	CHIME
SPICE SHAKER	1	3:4	TOP	NOPILL	NOSPOUT	DUMP	NOCHIME
SQ. CATCH-ALL	1	0	NOTOP	PILL	NOSPOUT	DUMP	NOCHIME
SUGAR BOWL	1	0	TOP	PILL	NOSPOUT	DUMP	CHIME
SUGAR COVER 2	2	0	NOTOP	NOPILL	NOSPOUT	DUMP	NOCHIME
SWAN	1	0	NOTOP	NOPILL	NOSPOUT	DUMP	NOCHIME
TAVERN SERVER	1	0	NOTOP	PILL	NOSPOUT	DUMP	NOCHIME
TEAPOT	1	0	TOP	PILL	SPOUT	DUMP	CHIME
TEDDY MUG	1	0	NOTOP	PILL	NOSPOUT	DUMP	NOCHIME
AutoMOST Expression Names:			**TP**	**PL**	**SPT**	**DMP**	**CHM**

Smooth	Lip	Slot	Notch	Padding	Diam. (in)	Slip weight (lbs)	Pour time (TMU)	Pour time (Sec)
SPONGE	NOLIP	NOSLOT	NONOTCH	FOAM	7.665	86.00	1575	56.65
SPONGE	LIP	NOSLOT	NONOTCH	NONE	8.665	25.10	695	25
SPONGE	NOLIP	NOSLOT	NONOTCH	NONE	5.53	17.90	695	25
SPONGE	NOLIP	NOSLOT	NONOTCH	CBOARD	2.8125	2.00	111	4
SPONGE	NOLIP	NOSLOT	NONOTCH	NONE	3.88	2.63	139	5
SPONGE	NOLIP	NOSLOT	NONOTCH	NONE	3.88	2.00	167	6.01
SPONGE	NOLIP	NOSLOT	NONOTCH	NONE	3.586	11.67	556	20
SPONGE	NOLIP	NOSLOT	NONOTCH	NONE	3.82	1.65	162	5.83
SPONGE	NOLIP	NOSLOT	NONOTCH	NONE	3.82	3.50	167	6
SPONGE	LIP	NOSLOT	NONOTCH	NONE	3.45	4.26	195	7.01
SPONGE	LIP	NOSLOT	NONOTCH	NONE	3.45	4.26	195	7.01
SPONGE	NOLIP	NOSLOT	NONOTCH	FOAM	5.8125	13.62	312	11.22
SPONGE	NOLIP	NOSLOT	NONOTCH	NONE	4.95	8.00	417	15
SPONGE	NOLIP	NOSLOT	NONOTCH	NONE	5.602	11.50	417	15
SPONGE	NOLIP	NOSLOT	NONOTCH	FOAM	4.22	8.75	334	12
SPONGE	LIP	NOSLOT	NONOTCH	NONE	4.709	6.21	220	7.91
SPONGE	LIP	NOSLOT	NONOTCH	CBOARD	4.709	6.21	220	7.91
SPONGE	LIP	NOSLOT	NONOTCH	NONE	4.709	6.21	220	7.91
SPONGE	LIP	NOSLOT	NONOTCH	CBOARD	4.709	6.21	220	7.91
FINGER	NOLIP	NOSLOT	NOTCH	NONE	2.7	1.72	139	5
FINGER	NOLIP	NOSLOT	NOTCH	NONE	2.7	1.72	139	5
SPONGE	NOLIP	NOSLOT	NONOTCH	NONE	NOSPARE	1.00	402	14.46
FINGER	NOLIP	NOSLOT	NONOTCH	NONE	1.1875	7.00	612	22
SPONGE	NOLIP	NOSLOT	NONOTCH	NONE	0.75	0.375	132	4.758
SPONGE	NOLIP	NOSLOT	NONOTCH	NONE	7.01	11.50	417	15
SPONGE	NOLIP	NOSLOT	NONOTCH	NONE	2.781	6.50	417	15
SPONGE	LIP	NOSLOT	NONOTCH	NONE	6.59375	12.25	417	15
SPONGE	NOLIP	NOSLOT	NONOTCH	NONE	5.3125	4.10	277	9.96
SPONGE	NOLIP	NOSLOT	NONOTCH	NONE	3.08	3.13	182	6.55
SPONGE	NOLIP	SLOT	NONOTCH	NONE	1.344	3.50	417	15
SPONGE	LIP	NOSLOT	NONOTCH	NONE	5.33	15.63	612	22
SPONGE	LIP	NOSLOT	NONOTCH	NONE	4.5125	11.10	417	15
FINGER	NOLIP	NOSLOT	NONOTCH	NONE	0.844	3.15	182	6.55
FINGER	NOLIP	NOSLOT	NONOTCH	NONE	0.844	3.15	182	6.55
SPONGE	NOLIP	NOSLOT	NONOTCH	NONE	8.117	29.14	973	35
SPONGE	NOLIP	NOSLOT	NONOTCH	NONE	0.9375	6.06	278	10
SPONGE	NOLIP	NOSLOT	NONOTCH	NONE	6.875	6.75	417	15
SPONGE	NOLIP	NOSLOT	NONOTCH	NONE	2.3125	3.65	278	10
FINGER	NOLIP	NOSLOT	NONOTCH	NONE	2.7	1.72	111	4
NONE	NOLIP	NOSLOT	NONOTCH	FOAM	4.875	5.25	207	7.44
SPONGE	NOLIP	NOSLOT	NONOTCH	NONE	4.5625	3.75	190	6.83
SPONGE	NOLIP	NOSLOT	NONOTCH	NONE	3.1875	10.50	556	20
SPONGE	NOLIP	NOSLOT	NONOTCH	NONE	2.75	1.50	160	5.76
SMOOTH	**LP**	**SLT**	**NCH**	**CB**	**DIAM**	**SW**	**POUR**	

```
Balancing Period :  8.00 Hours    Shortest Var: 98 TMU
Required Accuracy: +/-  5%        Longest Var : 158 TMU

-----------------------------------------------------------------
   Slot #  1   Allowed Deviation:18%       Occurrence: 650

                     Lower Limit:   98 TMU
                     Midpoint   :  115 TMU
                     Upper Limit:   133 TMU


-----------------------------------------------------------------
   Slot #  2   Allowed Deviation:15%       Occurrence: 650

                     Lower Limit:   133 TMU
                     Midpoint   :  145 TMU
                     Upper Limit:   158 TMU
```

FIGURE 5.9.3 R_t test for dumping a mold.

over 4.0 lb, the operator had more difficulty gaining control of and placing the molds. Table 5.9.3 shows a range of various mold weights, averaging approximately 6.80 kg (15 lb) with no slip and 10.4 kg (23 lb) when full. This data allowed the analysts to write applicator instructions for the respective dumping suboperations depending on the slip weight for a particular item.

The method of draining molds, however, was not limited to dumping. Some types of molds were drained and others had plugs. For any given piece, it was known which type of mold was used in the casting process. Molds are dumped in one of three ways: drained, dumped, or unplugged. Some cast items are not drained at all. In these cases, there is no dumping. Again,

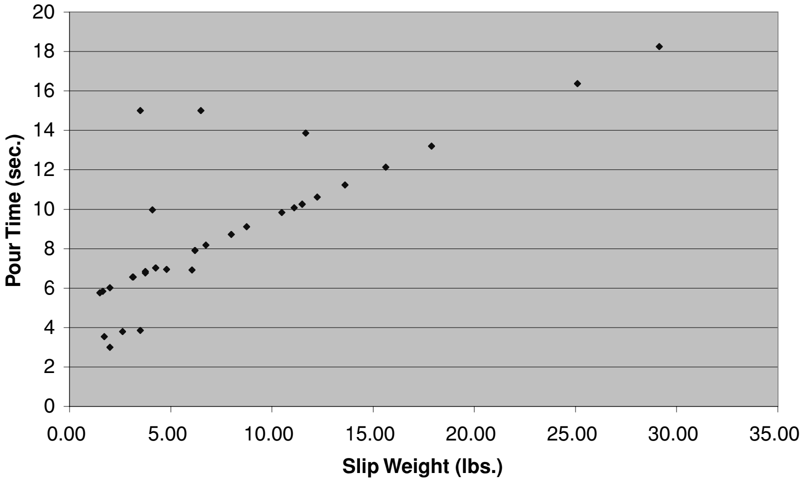


FIGURE 5.9.4 Slip weight versus pour time, regression graph.

TABLE 5.9.3 Average Casting Mold Weight

Item	Empty weight in pounds	Full weight in pounds
FOLK ART CREAMER	6.00	9.75
PREMIER SALT/PEPPER	9.25	12.25
TEA ROSE PEDESTAL MUG	10.25	13.38
YORKTOWNE PITCHER	28.00	43.50
AURA GRAVY BOAT	12.75	20.00
HERITAGE PITCHER	27.00	40.50
FOLK ART SOUP TUREEN	33.38	60.00
TROUSSEAU CREAMER	7.50	10.75
TEA ROSE CREAMER	10.68	14.63
FOLK ART SUGAR COVER	4.81	5.50
AVERAGE:	14.96	23.03

look at Table 5.9.2 and notice in the *Dump* column that a term has been assigned for every item. Items are classified as DRAIN, DUMP, NODUMP, or PLUG. Depending on which method is used to drain the molds, different work is required for the cast item. Also, some pieces are *chimed,* which means these items have a flanged ledge where a lid fits into place (gravy boats, soup tureens, teapots, etc.). When dumped, chimed molds need to be turned twice to ensure no slip has settled in the flange. To capture this additional work, a *Chimed* column was added to the key characteristics table and each piece labeled either CHIME or NOCHIME.

The team determined that based on which item was being cast, AutoMOST would look in the key characteristics table, find the appropriate item, and know which draining method was used. It would also know if that item had been chimed or not. AutoMOST would then add the appropriate suboperations at the proper frequencies. It is clear that this type of logic, applied with an expert system development tool such as AutoMOST, can drastically reduce the time required by an end user to set a standard. The team was now halfway through the casting operation and needed only one answer before setting a casting standard: the item to be cast.

Sparing. The next process in the casting standard is called *sparing,* which is removing any excess slip or flash from around the mold openings with a knife and/or scraper, then felting the piece in the mold with a sponge to smooth edges. The item, however, does not come out of the mold for the sparing process. This is done in the next phase, called *stripping.*

On observing the sparing process, it became evident that the larger the opening at the top of the mold, the longer it took an operator to spare. Also, if the item had a lip in the top (creamer, gravy boat, etc.), more care was required. Since sparing the mold was a variable element, again the first step was to create the simplest and most difficult cases as suboperations in MOST for Windows and run an R_t test. The results of the test showed that three suboperations were required to cover sparing. After continued observation, the analysts were able to create the three suboperations and code each with the appropriate applicator instructions. The first sparing suboperation covered any item with a mold opening diameter of less than or equal to 10.2 cm (4.0 in) with no lip. The second slot covered sparing items with an opening diameter of greater than 10.2 cm (4.0 in) but less than 15.2 cm (6.0 in) with no lip or less than or equal to 10.2 cm (4.0 in) with a lip. The final suboperation covered sparing molds with opening diameters greater than 15.2 cm (6.0 in) with no lip or greater than 10.2 cm (4.0 in) with a lip. Items with a spout (teapot, beverage server, etc.) required additional sparing. After sparing with a knife, items are felted by either smoothing with the operator's fingers or with a wet sponge, depending on the detail of the item.

After completing all the sparing suboperations, additional data was added to the key characteristics table (Table 5.9.2). A column was added showing the opening diameter for every mold. This data was available via drawings. Also, a column was added to show which items had a lip (LIP/NOLIP). Another column was added to describe how each item was smoothed, either by FINGERS or SPONGE. A final column was added to show which items had a spout by labeling each item either SPOUT or NOSPOUT.

Stripping. As the final phase of the casting standard, stripping was measured next. *Stripping* is the process of physically removing the item from the cast mold and asiding it onto a wooden board. This board full of wet items is then transported to the cast-finishing department.

The first observation the team made was that some molds housed two cast items (e.g., salt and pepper shakers, small bowl covers, lotion bottles, and candlesticks). This warranted developing a suboperation for stripping one piece from a mold as well as a suboperation for stripping two pieces. Again, this is tied to which item is being worked. Some items have a pill in the mold (see Fig. 5.9.2), some have a top that needs to be removed prior to stripping, and some must be placed on foam (as opposed to cardboard) on the take-away board. The respective suboperations from the top-down analysis were created, and columns were added to the key characteristics table showing which items had a pill in the mold (PILL/NOPILL), which had mold tops (TOP/NOTOP), and which needed to be placed on cardboard, foam, or no protective layer (FOAM/CBOARD/NONE).

The final activity category was titled *Miscellaneous.* Elements in this category did not fall into any of the other categories. For example, some items (e.g., salt and pepper shakers, spice shakers, bell ornaments) have holes and others do not. After stripping these items from their molds, the holes are created (punched). One of the items running at the time was a piggy bank that had a slot in the top. As with punching the holes, creating the slot requires a special tool. Finally, jam pot covers have a notch for a spoon that requires additional work when sparing. After carefully analyzing these miscellaneous and "exception" activities, the team added columns to the key characteristics table to show the number of holes in each item, which items had slots (SLOT/NOSLOT), and which had notches (NOTCH/NONOTCH).

AutoMOST Logic Tree Development

AutoMOST logic development involves two types of sessions: developer and end user. The AutoMOST developer creates the logic trees and, at the appropriate places, programs the system to add suboperations at specified or calculated frequencies. When the end user runs the tree (end-user session), the expert system asks the end user questions and adds suboperations and frequencies to the operation based on the end user's answers. AutoMOST then stores the Operation in MOST Data Manager.

The AutoMOST logic tree development at Pfaltzgraff was very straightforward since the core of the tree was the key characteristics table. The team had a finished table in Lotus 1-2-3, but the next task was to get the key characteristics table into a readable format and into AutoMOST. After reviewing the options, the team decided to use the table node in AutoMOST for the key characteristics table. The analysts added a final row to the key characteristics table in Lotus 1-2-3 (see Table 5.9.2) that shows the AutoMOST expression names for each characteristic—for example, POUR for pour time. The challenge was that all of the columns of the spreadsheet needed to go into one Custom Expression box in the table node. For the table node's Custom Expression box, the statement must be in the following format [6]:

```
EXPRESSION1:= 'STRING1' AND EXPRESSION2:= 'STRING2' AND...
```

To get the Lotus table into a working AutoMOST table format, the team simply added columns to the current spreadsheet table for the missing pieces such as the AND and the EXPRESSION1 := (see Table 5.9.4).

CASE STUDY: AUTOMATED STANDARD SETTING FOR CASTING AND CAST FINISHING OPERATIONS

TABLE 5.9.4 Excerpt of AutoMOST Formatted Key Characteristics Table

	Mold top		Pill in mold		Spout		Dump
TP:=’	TOP	‘AND PL:=’	NOPILL	‘AND SPT:=’	NOSPOUT	‘AND DMP:=’	DRAIN
TP:=’	NOTOP	‘AND PL:=’	PILL	‘AND SPT:=’	NOSPOUT	‘AND DMP:=’	DUMP
TP:=’	TOP	‘AND PL:=’	PILL	‘AND SPT:=’	NOSPOUT	‘AND DMP:=’	DUMP
TP:=’	NOTOP	‘AND PL:=’	NOPILL	‘AND SPT:=’	NOSPOUT	‘AND DMP:=’	DUMP
TP:=’	TOP	‘AND PL:=’	PILL	‘AND SPT:=’	NOSPOUT	‘AND DMP:=’	DUMP
TP:=’	TOP	‘AND PL:=’	PILL	‘AND SPT:=’	O SPOUT	‘AND DMP:=’	DUMP
TP:=’	TOP	‘AND PL:=’	PILL	‘AND SPT:=’	SPOUT	‘AND DMP:=’	DUMP
TP:=’	CSHALF	‘AND PL:=’	PILL	‘AND SPT:=’	NOSPOUT	‘AND DMP:=’	DUMP
TP:=’	CSHALF	‘AND PL:=’	PILL	‘AND SPT:=’	NOSPOUT	‘AND DMP:=’	DUMP
TP:=’	TOP	‘AND PL:=’	PILL	‘AND SPT:=’	NOSPOUT	‘AND DMP:=’	DUMP
TP:=’	NOTOP	‘AND PL:=’	PILL	‘AND SPT:=’	NOSPOUT	‘AND DMP:=’	DUMP
TP:=’	NOTOP	‘AND PL:=’	NOPILL	‘AND SPT:=’	NOSPOUT	‘AND DMP:=’	DRAIN
TP:=’	NOTOP	‘AND PL:=’	PILL	‘AND SPT:=’	NOSPOUT	‘AND DMP:=’	DUMP
TP:=’	NOTOP	‘AND PL:=’	PILL	‘AND SPT:=’	NOSPOUT	‘AND DMP:=’	DUMP
TP:=’	NOTOP	‘AND PL:=’	NOPILL	‘AND SPT:=’	NOSPOUT	‘AND DMP:=’	DRAIN
TP:=’	TOP	‘AND PL:=’	PILL	‘AND SPT:=’	NOSPOUT	‘AND DMP:=’	DUMP
TP:=’	NOTOP	‘AND PL:=’	PILL	‘AND SPT:=’	NOSPOUT	‘AND DMP:=’	DUMP
TP:=’	NOTOP	‘AND PL:=’	NOPILL	‘AND SPT:=’	NOSPOUT	‘AND DMP:=’	DUMP
TP:=’	NOTOP	‘AND PL:=’	NOPILL	‘AND SPT:=’	NOSPOUT	‘AND DMP:=’	DUMP
TP:=’	NOTOP	‘AND PL:=’	NOPILL	‘AND SPT:=’	NOSPOUT	‘AND DMP:=’	NODUMP
TP:=’	TOP	‘AND PL:=’	PILL	‘AND SPT:=’	NOSPOUT	‘AND DMP:=’	DUMP
TP:=’	NOTOP	‘AND PL:=’	NOPILL	‘AND SPT:=’	NOSPOUT	‘AND DMP:=’	DRAIN
TP:=’	NOTOP	‘AND PL:=’	PILL	‘AND SPT:=’	NOSPOUT	‘AND DMP:=’	DUMP
TP:=’	NOTOP	‘AND PL:=’	PILL	‘AND SPT:=’	NOSPOUT	‘AND DMP:=’	DUMP
TP:=’	NOTOP	‘AND PL:=’	PILL	‘AND SPT:=’	NOSPOUT	‘AND DMP:=’	DUMP
TP:=’	NOTOP	‘AND PL:=’	PILL	‘AND SPT:=’	NOSPOUT	‘AND DMP:=’	DUMP
TP:=’	NOTOP	‘AND PL:=’	PILL	‘AND SPT:=’	NOSPOUT	‘AND DMP:=’	DUMP
TP:=’	NOTOP	‘AND PL:=’	NOPILL	‘AND SPT:=’	NOSPOUT	‘AND DMP:=’	DUMP
TP:=’	NOTOP	‘AND PL:=’	PILL	‘AND SPT:=’	NOSPOUT	‘AND DMP:=’	DUMP
TP:=’	NOTOP	‘AND PL:=’	PILL	‘AND SPT:=’	NOSPOUT	‘AND DMP:=’	DUMP
TP:=’	TOP	‘AND PL:=’	NOPILL	‘AND SPT:=’	NOSPOUT	‘AND DMP:=’	DUMP

Next the spreadsheet was parsed to run all columns together but maintain the rows. Now the expressions were in the proper format for the AutoMOST Custom Expression box and were simply copied into the table node shown in Fig. 5.9.5.

The mechanics of the tree are very simple. Upon executing the table node, the tree asks the end user to choose a product (see Fig. 5.9.6). Once this choice is made, the tree uses the table node to assign all of the key characteristics to expressions that are later used in the procedural steps for routing through comparison nodes. Therefore, this is the only question the casting tree asks the end user. A major advantage to this approach is that all of the key characteristics are housed within one table node for maintenance purposes.

The tree uses a series of comparison nodes. These nodes look at the key characteristic expressions assigned in the table node to determine which branch to follow. Upon following a branch, AutoMOST automatically assigns the appropriate suboperations at the proper frequencies. The tree concludes once it has finished all the procedural steps for a casting standard: pouring, dumping, sparing, and stripping. The end user then has the option to save the standard. A sample casting operation is shown in Fig. 5.9.7.

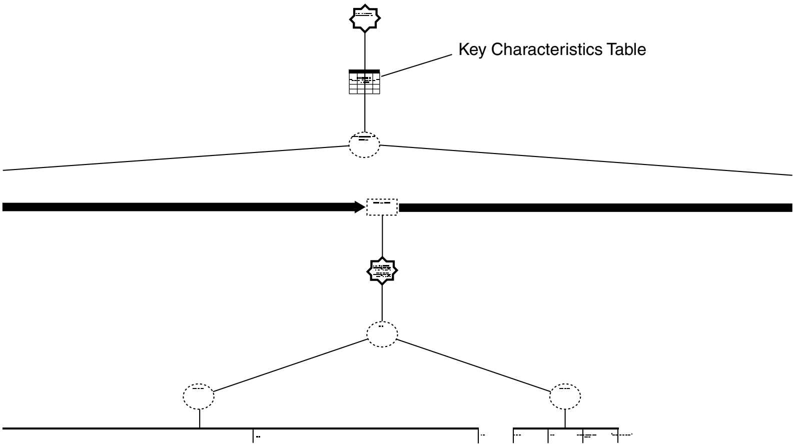
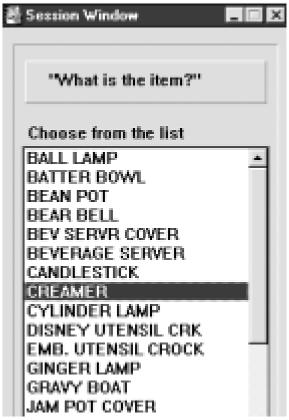


FIGURE 5.9.5 Casting key characteristics table in AutoMOST logic tree.



"What is the item?"

Choose from the list

- BALL LAMP
- BATTER BOWL
- BEAN POT
- BEAR BELL
- BEV SERVR COVER
- BEVERAGE SERVER
- CANDLESTICK
- CREAMER
- CYLINDER LAMP
- DISNEY UTENSIL CRK
- EMB. UTENSIL CROCK
- GINGER LAMP
- GRAVY BOAT
- JAM POT COVER

FIGURE 5.9.6 End-user session of AutoMOST logic tree.

CAST-FINISHING OPERATIONS

Similar to casting operations, cast finishing consists of a series of common operations:

1. *Trimming*

   Operator trims around top, bottom, sides, handles, and spouts of item to remove any seams.
2. *Wet-sponging*

   Item is wet-sponged all over and along seam.
3. *Flushing*

   Item is moved to a flushing machine and flushed with water.
4. *Decorating*

   Item is either stamped or banded.

Top-Down Analysis

Since the casting and cast-finishing departments were designated to be the "top" in the top-down analysis, the elements for cast finishing are included in the element list in Table 5.9.1. After a few hours of observation, the team was able to classify each cast-finishing element as either *constant* or *variable* and begin to develop the data.

As with the casting department, many of the characteristics that drove different types of work were associated with the cast item. For instance, all of the sponging around the seam and cleaning time depends on the lineal perimeter distance of the seam and whether the item has a spout, handle, lip, or combinations of these. Also, some items have a top that gets trimmed and some do not. Some items, such as a small mug, have a very small handle compared to the one on a beverage server. With these and many other identifiers for each cast-finishing process in mind, the team decided to create a table that would store all of the key characteristics associated with each item for the cast-finishing process (see Table 5.9.5). Using the same principle applied in casting, this table would be read by AutoMOST and used to pick the appropriate suboperations for the cast-finishing process.

Operation report–Combined report
Pfaltzgraff/Thomasville

Oper ID: 11022 Status: Public
Description: CAST (SINGLE CAVITY)
Plant: 01 Facility:11 Routing No: 11078
Routing Desc: 18902490
Routing Chg. No: Routing Note:
Oper. Seq. No: 010 Dept: 0060 Work Center: 0010
Oper Number: 01001 Yield: .98
Crew Rate: 71.07 Crew Size: 1.0
Standard Code: P Worksheet ID:
IE: MCS Issue: 1
Create Date: 10/2/96 Effective Date: 10/2/96

Step	Sub-op ID	Description	Freq	Time	Internal to
1	116	HOLD+MOVE PC. 1-2 STEPS	1.0	0.00040	
2	MO	POURING PROCESS TIME	1.0	0.00195	
3	735	WALK BETWEEN ROWS	1.0	0.00002	
4	694	SETUP HOSE & SCOOP FOR POURING	2/650	0.00002	
5	695	CLEAN SCOOP	1/650	0.00001	
6	700	DUMP MOLD (SW >= 4.00 LBS.)	1.0	0.00142	
7	701	TURN MOLD	1.0	0.00060	
8	735	WALK BETWEEN ROWS	1.0	0.00002	
9	714	SCRAPE TOP OF MOLD	1.0	0.00031	
10	715	LOWER MOLD TO SPARE AND RETURN IT TO SHELF	1/5	0.00024	
11	713	SPARE MOLD (DIAM =4.1 TO 6″ NO LIP OR DIAM <=4″ WITH LIP)	1.0	0.00158	
12	717	SMOOTH WITH FINGERS AFTER SPARING	2	0.00060	
13	723	GENERAL FELTING	1.0	0.00089	
14	735	WALK BETWEEN ROWS	1.0	0.00004	
15	731	SETUP EMPTY BOARDS FOR CASTING (SIMPLEST)	1/2	0.00005	
16	732	SETUP EMPTY BOARDS FOR CASTING (MOST DIFFICULT)	1/2	0.00032	
17	729	STRIP 1 PIECE FROM MOLD	1.0	0.00254	
18	707	CLEAN & RE-ASSEMBLE PILL INTO MOLD	1.0	0.00070	
19	735	WALK BETWEEN ROWS	1.0	0.00002	

Type of work	Elemental time	Allowance percent	Allowance time	Standard time
External manual	0.00976	16	0.00156	0.01132
Assigned internal	0.00000	16	0.00000	0.00000
Process time	0.00195	41	0.00080	0.00275
Std (hrs/cycle)	0.01171		0.00236	0.01407

Pieces/cycle: 1
Standard (hrs/piece): 0.01407
(Pieces per hr @ 100%): 71.06855

FIGURE 5.9.7 Sample casting standard.

TABLE 5.9.5 Cast-Finishing Key Characteristics Table

Item	Flush	Band PT	Stamp	Band	Stoned	Trim top	Trim base	Slip weight (lbs)
BALL LAMP	NOFLUSH	0	NOSTAMP	NOBAND	NOSTONE	NOTRTOP	TRBASE	86.00
BATTER BOWL	FLUSH	265	SOME	SOME	SOME	TRTOP	TRBASE	25.10
BEAN POT	FLUSH	112	SOME	SOME	SOME	NOTRTOP	TRBASE	17.90
BEAR BELL	NOFLUSH	0	SOME	NOBAND	NOSTONE	NOTRTOP	TRBASE	2.00
BEV SERVR COVER	FLUSH	73	NOSTAMP	SOME	NOSTONE	NOTRTOP	TRBASE	2.00
BEVERAGE SERVER	FLUSH	112	SOME	SOME	SOME	NOTRTOP	TRBASE	11.67
CANDLESTICK	NOFLUSH	73	SOME	SOME	SOME	TRTOP	TRBASE	1.65
CREAMER	FLUSH	112	SOME	SOME	SOME	TRTOP	TRBASE	4.26
CYLINDER LAMP	NOFLUSH	0	NOSTAMP	NOBAND	NOSTONE	NOTRTOP	NOTRBASE	13.62
DISNEY UTENSIL CRK	FLUSH	0	NOSTAMP	NOBAND	NOSTONE	TRTOP	TRBASE	8.00
EMB. UTENSIL CROCK	FLUSH	112	SOME	SOME	NOSTONE	TRTOP	TRBASE	11.50
GINGER LAMP	NOFLUSH	0	SOME	NOBAND	NOSTONE	NOTRTOP	TRBASE	8.75
GRAVY BOAT	FLUSH	112	SOME	SOME	SOME	TRTOP	TRBASE	6.21
JAM POT COVER	FLUSH	0	NOSTAMP	NOBAND	NOSTONE	NOTRTOP	NOTRBASE	1.72
LADLE	NOFLUSH	0	NOSTAMP	NOBAND	NOSTONE	NOTRTOP	NOTRBASE	1.00
LOTION BOTTLE	FLUSH	0	SOME	NOBAND	NOSTONE	TRTOP	TRBASE	7.00
LOTION BOTTLE TOP	NOFLUSH	0	NOSTAMP	NOBAND	NOSTONE	NOTRTOP	NOTRBASE	0.375
MAIL BASKET	FLUSH	220	SOME	SOME	NOSTONE	TRTOP	TRBASE	11.50
MILK BOTTLE	FLUSH	0	NOSTAMP	NOBAND	NOSTONE	TRTOP	TRBASE	6.50
MINI BATTER BOWL	FLUSH	161	SOME	SOME	NOSTONE	TRTOP	TRBASE	12.25
ONION SOUP	FLUSH	73	SOME	SOME	NOSTONE	TRTOP	TRBASE	4.10
PEDESTAL MUG	FLUSH	73	SOME	SOME	SOME	TRTOP	TRBASE	3.13
PIGGY BANK	NOFLUSH	0	SOME	NOBAND	NOSTONE	NOTRTOP	NOTRBASE	3.50
PITCHER (1.75 QT.)	FLUSH	220	SOME	SOME	NOSTONE	TRTOP	TRBASE	15.63
PITCHER (1 QT.)	FLUSH	161	SOME	SOME	SOME	TRTOP	TRBASE	11.10
SALT/PEPPER	NOFLUSH	73	SOME	SOME	SOME	NOTRTOP	TRBASE	3.15
SOUP TUREEN	FLUSH	220	SOME	SOME	NOSTONE	NOTRTOP	TRBASE	29.14
SPICE SHAKER	FLUSH	73	NOSTAMP	NOBAND	SOME	NOTRTOP	TRBASE	6.06
SPICE SHAKER	NOFLUSH	73	NOSTAMP	NOBAND	SOME	NOTRTOP	TRBASE	6.06
SQ. CATCH-ALL	FLUSH	265	SOME	SOME	NOSTONE	TRTOP	TRBASE	6.75
SUGAR BOWL	FLUSH	0	NOSTAMP	NOBAND	NOSTONE	NOTRTOP	NOTRBASE	3.65
SUGAR COVER	NOFLUSH	0	NOSTAMP	NOBAND	NOSTONE	NOTRTOP	NOTRBASE	1.72
SWAN	NOFLUSH	0	NOSTAMP	NOBAND	NOSTONE	NOTRTOP	TRBASE	5.25
TAVERN SERVER	FLUSH	73	SOME	SOME	NOSTONE	NOTRTOP	TRBASE	3.75
TEAPOT	FLUSH	112	SOME	SOME	NOSTONE	NOTRTOP	TRBASE	10.50
TEDDY MUG	FLUSH	73	NOSTAMP	SOME	NOSTONE	TRTOP	TRBASE	1.50
AutoMOST Expression	**FLSH**	**BNDPT**	**STMP**	**BND**	**STONE**	**TRT**	**TRB**	**SW**

CASE STUDY: AUTOMATED STANDARD SETTING FOR CASTING AND CAST FINISHING OPERATIONS

Item size	# Handles	Handle size (trimming)	Handle size (sponging)	Base diameter	Lineal inches side	Spout	Lip	Top diameter
LARGE	0	NOHANDLE	NOHANDLE	3.531	14.64	NOSPOUT	NOLIP	7.665
LARGE	1	MHANDLE	LHANDLE	5.738	5.918	NOSPOUT	LIP	8.665
LARGE	2	SHANDLE	MHANDLE	5.875	6.375	NOSPOUT	NOLIP	5.53
SMALL	0	NOHANDLE	NOHANDLE	2.812	3.656	NOSPOUT	NOLIP	2.8125
SMALL	0	NOHANDLE	NOHANDLE	3.88	3	NOSPOUT	NOLIP	3.88
MEDIUM	1	LHANDLE	LHANDLE	4.446	7.688	SPOUT	NOLIP	3.586
SMALL	0	NOHANDLE	NOHANDLE	3.56	4.61	NOSPOUT	NOLIP	3.82
SMALL	1	SHANDLE	MHANDLE	3.072	4.74	NOSPOUT	LIP	3.45
LARGE	0	NOHANDLE	NOHANDLE	3.5	11	NOSPOUT	NOLIP	5.8125
MEDIUM	2	SHANDLE	NONE	4.343	7.647	NOSPOUT	NOLIP	4.95
MEDIUM	0	NOHANDLE	NOHANDLE	5.141	7.655	NOSPOUT	NOLIP	5.602
MEDIUM	0	NOHANDLE	NOHANDLE	2.938	7.11	NOSPOUT	NOLIP	4.22
SMALL	1	SHANDLE	MHANDLE	3.51	3.97	NOSPOUT	LIP	4.709
SMALL	0	NOHANDLE	NOHANDLE	2.7	2.319	NOSPOUT	NOLIP	2.7
SMALL	0	NOHANDLE	NOHANDLE	3	6	NOSPOUT	NOLIP	NOSPARE
MEDIUM	0	NOHANDLE	NOHANDLE	2.28	5.78	NOSPOUT	NOLIP	1.1875
SMALL	0	NOHANDLE	NOHANDLE	2.889	1.5	NOSPOUT	NOLIP	0.75
LARGE	0	NOHANDLE	NOHANDLE	6.898	5.025	NOSPOUT	NOLIP	7.01
MEDIUM	0	NOHANDLE	NOHANDLE	3.616	8.834	NOSPOUT	NOLIP	2.781
MEDIUM	1	MHANDLE	MHANDLE	4.344	5.281	NOSPOUT	LIP	6.59375
SMALL	1	MHANDLE	NONE	3.688	2.469	NOSPOUT	NOLIP	5.3125
SMALL	1	SHANDLE	SHANDLE	3.027	5.513	NOSPOUT	NOLIP	3.08
SMALL	0	NOHANDLE	NOHANDLE	1.344	6.499	NOSPOUT	NOLIP	1.344
LARGE	1	LHANDLE	LHANDLE	5.06	9.55	NOSPOUT	LIP	5.33
MEDIUM	1	MHANDLE	MHANDLE	4.278	5.98	NOSPOUT	LIP	4.5125
NONE	0	NOHANDLE	NOHANDLE	0.844	4.36	NOSPOUT	NOLIP	0.844
LARGE	2	SHANDLE	NONE	7.2	6.916	NOSPOUT	NOLIP	8.117
SMALL	1	SHANDLE	MHANDLE	0.9375	7.125	NOSPOUT	NOLIP	0.9375
SMALL	1	SHANDLE	MHANDLE	0.9375	7.125	NOSPOUT	NOLIP	0.9375
MEDIUM	0	NOHANDLE	NOHANDLE	4.937	4.281	NOSPOUT	NOLIP	6.875
SMALL	0	NOHANDLE	NOHANDLE	4.25	4.5	NOSPOUT	NOLIP	2.3125
SMALL	0	NOHANDLE	NOHANDLE	2.7	2.319	NOSPOUT	NOLIP	2.7
SMALL	0	NOHANDLE	NOHANDLE	4.875	7.975	NOSPOUT	NOLIP	4.875
SMALL	0	NOHANDLE	NOHANDLE	3.43	3.475	NOSPOUT	NOLIP	4.5625
MEDIUM	1	MHANDLE	MHANDLE	4.204	4.86	SPOUT	NOLIP	3.1875
SMALL	2	SHANDLE	SHANDLE	2.75	3.309	NOSPOUT	NOLIP	2.75
SIZE	**HANDLES**	**HNDSIZE**	**SPNHND**	**BSEDIAM**	**LININ**	**SPT**	**LP**	**DIAM**

Data Collection and Suboperation Development

Trimming. Data collection began for the first activity for a cast-finishing operation: *trimming.* Again, this is the process in which the operator obtains a knife and trims all the way around the item to hide the presence of any seam. The lineal perimeter distance trimmed directly influences this procedure. This process is complicated further if the item being trimmed has a handle, spout, or lip. The perimeter for the sides of each item was obtained from drawings. The time to trim around the top and/or base of an item depended on the diameter of the opening on the top and the diameter of the base of the item. Again, this was obtained from drawings.

The team began by looking at the simplest and most difficult cases of trimming the side of an item (excluding the inside), trimming of handles, and trimming of spouts. The R_t results showed that two suboperations were necessary. The team then created the two suboperations and determined that if the perimeter of the seam on one side of an item was less than or equal to 30.5 cm (12 in), the first suboperation applied. Conversely, if the perimeter of the seam on a side was greater than 30.5 cm (12 in), the second suboperation applied. Applicator instructions stating these conditions were added to the suboperations, which were filed into the MOST for Windows® database. Next, the team looked at trimming the top or bottom of an item. As previously stated, this was based on the diameter of the top or bottom and whether the item had a lip in the top. Since this was a variable element, suboperations were developed for the simplest and most difficult cases of trimming around the top or bottom of an item. R_t testing then showed that three suboperations were needed to cover all variations between the simplest and most difficult cases. These three were created, and it was discovered that the first suboperation covered items with a top or bottom diameter less than or equal to 10.8 cm (4.25 in) with no lip. The second covered items with a top diameter of 10.81 cm (4.26 in) to 17.8 cm (7.0 in) with no lip, items with a lip and a top diameter of less than or equal to 10.2 cm (4.0 in), or items with a bottom diameter between 10.81 cm (4.26 in) and 17.8 cm (7.0 in). The third and final suboperation covered items with no lip and a top diameter greater than 17.8 cm (7.0 in), items with a lip and top diameter greater than 10.2 cm (4.0 in), or trimming the bottom of an item with bottom diameter greater than 17.8 cm (7.0 in).

At this point, columns were added to the key characteristics table to show the lineal inches of the following: (1) one side for every item, (2) the top diameter in inches, (3) whether the item had a LIP or NOLIP, (4) the base diameter in inches, (5) an identifier for whether the item required the top to be trimmed (TRTOP/NOTRTOP), and (6) an identifier for whether the item required the bottom to be trimmed (TRBASE/NOTRBASE). These additions are shown in Table 5.9.5.

The analysts then observed the trimming of handles and spouts on an item. Again, the suboperations were created and the key characteristics added to the table. The next phases of the trimming process observed were blowout, stoning the foot, and re-reaming holes. *Blowout* is air-cleaning the part to remove any debris. *Stoning the foot* is the process of sliding the base of the item over a gritty surface to make the bottom rough. This is mainly so the item will not stick to the tray when fired in the oven. *Re-reaming* holes in an item is the process of running a metal prong down through all of the holes to ensure that they have not been clogged by debris, excess slip, or trimmings. Following the same technique, suboperations were created for blowing out items, stoning the foot, and re-reaming holes, and the appropriate columns were added to the key characteristics table.

Wet-Sponging. Following the trimming phase, the analysts moved to the next phase of the cast-finishing operation: *wet-sponging* the item. As with trimming, the suboperations here were divided into wet-sponging the seam, top, bottom, handle, and spout. Wet-sponging involved wiping the whole item, wiping the top and bottom, wiping the seams and spouts, and wiping the handles. Among the characteristics added to the table were lineal inches around the seam and handle and spout characteristics. Again, this information was obtained from drawings.

Flushing. The next phase of the cast-finishing operation is *flushing.* Each piece is glaze-flushed to ensure the inside of the piece gets covered with glaze. Flushing time is based solely on the size of the item, so suboperations were created and a column added to the table for the size of the item (SMALL, MEDIUM, LARGE) and another column for FLUSH or NOFLUSH.

Decoration. The final phase in the cast finishing process is *decorating.* The only types of decorating performed in the cast-finishing department are stamping the item with an ink stamp or running a band around the item on a turntable. Stamping requirements vary by item. Since stamping is a constant element, two suboperations were created: one for stamping one stamp on an item and one for stamping two stamps on an item. A new column labeled *Stamp* was added to the key characteristics table to identify each item as NOSTAMP or SOME. If the item was labeled SOME, AutoMOST would have to ask the user whether the item should receive a stamp, and if so, how many.

The banding process consists of setting up the item on the banding turntable, placing the brush to the item, and processing time for the band to go around the item. Since this is a variable element, the simplest and most difficult cases were created, and R_t tests showed that six slots were required—the only difference between the slots being the different representative process times. Two new columns were added to the key characteristics table, labeled *Band* and *BandPT.* As with stamping, some items received no banding. Other items had variations that received banding and variations that did not. Rather than list all variations, each item was labeled NOBAND or SOME in the *Band* column of the table. For an item classified as SOME, AutoMOST would ask if that specific item needed to be banded. The *BandPT* column contained the representative process time for the banding of each item.

AutoMOST Logic Tree Development

Again, the AutoMOST logic tree development was very straightforward since, as with the casting tree, the core of the tree was the key characteristics table. The team followed the principles illustrated in the casting tree and used the table node in AutoMOST for the key characteristics table. The analysts added a final row to the cast-finishing key characteristics table in Lotus 1-2-3 (see Table 5.9.5), which showed the AutoMOST expression names for each characteristic—for example, BSEDIAM for base diameter.

The same process of parsing the key characteristics table explained earlier was then used to get the table into the proper AutoMOST syntax. This information was then copied into the table node.

The cast-finishing tree works like the casting tree, with a few exceptions. On executing the table node, the tree asks the end user to choose a product. Once this choice is made, the tree uses the table node to assign all of the key characteristics to expressions that are later used in the procedural steps for routing through comparison nodes. The difference here is that with some products the expert system needs to ask for more information (e.g., "Does this variation of the beverage server receive a band?"). Even with these extra questions, the cast-finishing tree asks a maximum of four questions for any item produced.

In the same manner as the casting tree, upon following a branch, AutoMOST automatically assigns the appropriate suboperation(s) at the proper frequencies. The tree concludes once it has finished all of the procedural steps for a cast-finishing standard: trimming, wet-sponging, flush, wipe top, and decorate. The end user then has the option to save the standard. A sample cast-finishing standard can be seen in Fig. 5.9.8.

STANDARD DATA VALIDATION

Upon completing and testing the logic trees, the standard data was tested in systematic and random situations to ensure that, once the balancing time (2 minutes) was met, the standards were within the desired level of accuracy (±5%). This level of accuracy was acceptable to Pfaltzgraff since the Associates' incentive is calculated weekly. A sample validation is shown in Table 5.9.6.

Operation report–Combined report
Pfaltzgraff/Thomasville

Oper ID: 11023 Status: Public
Description: FINISH
Plant: 01 Facility:11 Routing No: 11078
Routing Desc: 18902490
Routing Chg. No: Routing Note:
Oper. Seq. No: 020 Dept: 0064 Work Center: 0100
Oper Number: 02000 Yield: .94
Crew Rate: 50.64 Crew Size: 1.0
Standard Code: P Worksheet ID:
IE: SKG Issue: 6
Create Date: 11/24/98 Effective Date: 10/2/96

Step	Sub-op ID	Description	Freq	Time	Internal to
1	743	MOVE BOARDS AT CAST FINISHING	1.0	0.00008	
2	744	OBTAIN AND ASIDE ITEM FOR CAST FINISHING	1.0	0.00059	
3	747	TRIM HANDLE AT CAST FINISHING (SMALL HANDLE)	1.0	0.00100	
4	750	TRIM TOP OR BOTTOM OF PIECE FOR CAST FINISHING	1.0	0.00030	
5	751	TRIM TOP OR BOTTOM OF PIECE FOR CAST FINISHING	1.0	0.00055	
6	753	TRIM SIDE OF PIECE FOR CAST FINISHING (LIN.IN. <=12″)	1.0	0.00040	
7	755	BLOWOUT PIECE AT CAST FINISHING (SMALL PIECE)	1.0	0.00019	
8	744	OBTAIN AND ASIDE ITEM FOR CAST FINISHING	1.0	0.00059	
9	758	STONE ITEM AT CAST FINISHING	1.0	0.00030	
10	744	OBTAIN AND ASIDE ITEM FOR CAST FINISHING	1.0	0.00059	
11	776	WASH-RINSE PIECE AND WET-SPONGE ALL THE WAY AROUND	1.0	0.00084	
12	778	WET-SPONGE HANDLE WITH SPONGE-ON-ROD (SPNHND=MEDIUM)	1.0	0.00150	
13	780	WET-SPONGE TOP OR BOTTOM OF PIECE (SIZE=SMALL, MEDIUM, NONE)	2	0.00110	
14	785	WET-SPONGE SEAM WITH SPONG (LIN. IN 3.71″-4.75″)	3.500	0.00592	
15	743	MOVE BOARDS AT CAST FINISHING	1.0	0.00008	
16	789	CLEAN BOARDS AT CAST FINISHING	1.0	0.00002	
17	744	OBTAIN AND ASIDE ITEM FOR CAST FINISHING	1.0	0.00059	
18	790	FLUSH PIECE AT CAST FINISHING (SIZE=SMALL)	1.0	0.00090	
19	744	OBTAIN AND ASIDE ITEM FOR CAST FINISHING	1.0	0.00059	
20	792	WET SPONGE EXCESS FLUSH FROM TOP OF PIECE AT CF	1.0	0.00090	

FIGURE 5.9.8 Sample cast-finishing standard.

Type of work	Elemental time	Allowance percent	Allowance time	Standard time
External manual	0.01703	16	0.00272	0.01975
Assigned internal	0.00000	16	0.00000	0.00000
Process time	0.00000	41	0.00000	0.00000
Std (hrs/cycle)	0.01703		0.00272	0.01975

Pieces/cycle: 1
Standard (hrs/piece): 0.01975
(Pieces per hr @ 100%): 50.63548

FIGURE 5.9.8 Sample cast-finishing standard. (Continued)

RESULTS

From the case study presented here, it is clear that this type of automated standard-setting technique has many advantages in situations with highly variable parts where this level of accuracy is required (incentive systems). First, from an AutoMOST developer's viewpoint, it is critical to begin with the end in mind and think ahead throughout the development. The analysts should always be thinking of how easy or difficult it will be to set a standard. If a front-end knowledge-based expert system such as AutoMOST will be used, it is important to experiment with how the logic will work up front and as data development progresses. This way, any mistakes in the thought process can be corrected immediately. It is not useful to ask questions of an end user that cannot be easily answered. Thinking ahead into logic development enables an analyst or team to create many standards in a short period of time and therefore more cost-effectively.

TABLE 5.9.6 Standard Data Validation

	Operation	Actual time leveled	Standard time	+/–	+/–
1	Scrape top of mold (salt shaker)	35	30	–5	–14.29%
2	Spare mold (creamer)	247	240	–7	–2.83%
3	Turn mold (gravy boat)	50	60	10	20.00%
4	Strip 0429 ped mug (has pill)	320	290	–30	–9.38%
5	Strip 05024 creamer (no pill)	205	220	15	7.32%
6	Pour 10378 teapot	567	556	–11	–1.94%
7	Dump teapot	107	120	13	12.15%
8	Turn beanpot	58	60	2	3.45%
9	Scrape beanpot	30	30	0	0.00%
10	Spare teapot	295	282	–13	–4.41%
11	Spare mold (smaller creamer)	166	180	14	8.43%
12	Strip mold (swans)	263	220	–43	–16.35%
13	Turn mold (milk bottle)	75	60	–15	–20.00%
14	Spare mold (milk bottle—difft oper.)	112	142	30	26.79%
15	Dump mold (gravy boat)	88	100	12	13.64%
16	Strip mold (4290 ped mug with pill)	262	290	28	10.69%
17	Strip mold (teapot with pill and top)	515	430	–85	–16.50%
18	Spare mold (teapot)	227	204	–23	–10.13%
19	Addt'l sponging of teapot (spout, rim)	333	400	67	20.12%
		3955	3914	–41	–1.04%

Second, quite often the information needed to make part-characteristic trees of this type exists somewhere in a computer system or filing cabinet. The trees presented in this case study accessed key characteristic information from within the trees, but that information could have been kept outside of the trees and maintained in a spreadsheet or database. Depending on the application and end users, this is useful in certain situations. It may take some time and some searching to compile all of the information, but, once finished, great benefits will be realized.

A third major advantage to the AutoMOST developer is that with these types of trees, all of the part characteristics are in one place in the tree. This provides easy maintenance as characteristics change or as parts are added to or deleted from production. When a new part is added, the AutoMOST developer can add that part to the table along with its key characteristics. No additional tree maintenance is required.

Finally, Pfaltzgraff realized many advantages from this type of end-user, standard-setting application—such as speed and consistency. On average, a casting or cast-finishing standard can be set in under 3 minutes, freeing up valuable IE time. Without a front-end expert system, setting a standard of this nature could take as long as 30 minutes. Also, inputs coming from a table instead of being manually entered on a keyboard provide less chance for applicator error. This means the standards will be more consistent. With AutoMOST automatically adding the correct suboperations to the standard at the proper frequencies, the desired level of accuracy is maintained.

In summary, applications of this type benefit both the AutoMOST developer and the end user, creating a win-win situation. The developer benefits by being forced to think through the development of a standard, gather the necessary information, and keep all inputs in one place, thus minimizing tree maintenance. Benefits to the end users include minimal questions, consistency when multiple users are setting standards, and maintaining the desired level of accuracy. Although this case study exemplifies a very specialized manufacturing area, the approach is quite similar for applications in other areas (e.g., general assembly). From the information presented in this case study, it is evident that expert system logic trees coupled with part-characteristic tables can greatly simplify setting standards for highly variable parts when a logic pattern can be identified.

ACKNOWLEDGMENTS

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FURTHER READING

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Connors, John, *Standard Data Concepts and Development.*

BIOGRAPHY

Jeffrey A. Arnold is a senior consultant with H. B. Maynard and Co., Inc. He was responsible for the labor standards project at Pfaltzgraff and has extensive work measurement and AutoMOST experience across a wide spectrum of industries, including automotive, retail, distribution, aerospace, and lean manufacturing. Mr. Arnold has provided productivity solutions to clients and managed projects both domestically and internationally. He is a native of Pittsburgh, Pennsylvania, and received his B.S. in Engineering Management from Grove City College in Pennsylvania.

Source: MAYNARD'S INDUSTRIAL ENGINEERING HANDBOOK

CHAPTER 5.10

CASE STUDY: LABOR STANDARDS FOR LONG-CYCLE JOBS IN THE AEROSPACE INDUSTRY

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In the 1980s and early 1990s, the United States Department of Defense required defense contractors to implement engineered labor standards systems for performance management and costing practices in the defense industry. This requirement led to the overhaul of labor control systems for many defense contractors and their suppliers. Today, this MIL-STD requirement has been relaxed, but contractors maintain these systems because they are the infrastructure for good operations management.

The application of engineered standards to low-volume, long-cycle operations requires that industrial engineers fully use statistical principles and state-of-the-art tools to make the standard setting process as simple and economical as possible. This case study describes the process used at Boeing (formerly McDonnell Douglas) in St. Louis, Missouri, to apply engineered standards to their military aircraft production operations.

BACKGROUND AND APPROACH

Cycle time for manufacturing a fighter aircraft spans many months. The labor-hour content itself is in the thousands of hours. It can be overwhelming to develop accurate (Type I) standards for such big assemblies with very low rate production and a very long manufacturing cycle. It was an extremely challenging task to create labor standards within ±10 percent accuracy and 90 percent confidence level for manual assembly operations. These engineered standards had to be objective, verifiable, and traceable besides meeting the accuracy levels defined in MIL-STD 1567A.

Long-cycle assembly jobs tend initially to overwhelm us. In the aerospace industry, it seems that these operations get longer and longer and the volumes get smaller and smaller. If industrial engineers were not constantly finding ways to improve their effectiveness, this would result in higher engineering/administrative costs as a percentage of revenue.

Closer analysis of long-cycle assembly operations results in the conclusion that there is actually no such thing as a long assembly operation. It is all a matter of how you look at the operation. Long assembly operations are simply the sum of many repeated short assembly tasks. This conclusion leads us to adopt what is normally called a *standard data approach* to establishing labor standards for these "long" operations.

In very simple terms, this approach involves establishing standard times for unique, repetitive tasks and combining these times in the proper order and frequency to reflect long operations.

ORGANIZATION OF PROJECT

Engineering Team

People are the most valuable asset of any organization. It is extremely important to have a motivated and skilled workforce with the right attitude and training. Management assembled a team of industrial engineers, including a mix of experienced IEs and fresh college graduates, and provided the necessary training to the whole group. This group was charged with the task of developing engineered standards for over 1 million aircraft manufacturing operations, ranging in time from those lasting a few minutes to those extending over multiple shifts.

Software and Hardware

The magnitude of scale of the standards effort made it necessary to utilize computer applications to establish new labor standards. After many surveys and benchmarking efforts, the company selected the Maynard Operation Sequence Technique, a computerized predetermined work measurement system commonly known as MOST® (a registered trademark of H. B. Maynard and Company, Inc., in Pittsburgh, Pennsylvania).

Fabrication and assembly operations are performed in numerous buildings apart from each other. This created a potential for problems with communication and duplication of effort. To avoid this, the industrial engineers were all linked together through the local area network, which enabled them to share a single database of standard data.

Training

One hundred industrial engineers and their immediate supervisors were required to go through classroom training to learn the system for developing standards.

Simultaneously, the first-line shop supervisors and their upper management were given an overview of the system and made aware of the future impact on their performance metrics. This overview answered most of the doubts about the standards initiative and demonstrated management commitment to the project. This turned out to be very important to the success of the project.

Project Teams

The industrial engineers were organized in teams of 10, with one lead industrial engineer assigned to each group. In addition to these teams, one group of data coordinators was also formed. The primary function of data coordinators was to make sure that as soon as standard data was developed, it was added to the proper database with the correct attributes and made available to all the users. This eliminated duplication of effort among the IEs in all the teams. The other key responsibility of the data coordinator group was to track progress and keep all personnel and management informed of project status.

PROCEDURE AND APPLICATION OF TOOLS

After the classroom training, the real analysis began. The first step in the process of developing standard data was called *top-down analysis.* This analysis resulted in a standard data structure consisting of all of the repeatable activities that were later to be combined to reflect larger assembly operations.

Long assembly sequences are normally comprised of a variety of activities or processes that, when combined, make up the entire task. These unique activities or processes are repeated until the entire task is complete.

It is very important to complete the top-down analysis before beginning the work measurement task. Top-down analysis results in a data structure that initially minimizes the standard data development effort and later facilitates application of the standard data to establish time standards. The top-down analysis for assembly operations at Boeing identified the following major categories of work:

- Assembly of structural parts
- Drilling
- Installation of various fasteners
- Cleaning
- Application of sealer
- Installing harnesses and cable assemblies
- Splicing and wire terminations
- Installing tubing and hoses
- Installing clamps, fittings, couplings, and so on

These categories were used to list all of the subtasks (or suboperations) representing unique work activities.

The objective of the standard data approach is to measure each different activity one time, then store the results in the database so that they can be combined with other activities to represent higher-level tasks, which in turn can be combined to establish labor standards for the entire assembly.

To better define the methodology, we can use the example of *assembly of structural parts.* The following sequence of events takes place when assembling components to the fuselage structure of a fighter airplane:

1. Obtain the part from the kit.
2. Verify the part number.
3. Unpack and recycle the packing material.
4. Position the part in structure.
5. Hold the part in structure using temporary fasteners.

These activities result in the part being located to the fixture and held in place with temporary fasteners (prior to drilling holes for fastening the part to the assembly). We find that there are a number of ways that each of these five activities can be performed. These are called *variable* *activities,* each of which can range from simple to difficult. We can look at each of these activities and determine the nature of the variability of the activity.

1. *Obtain the part from the kit.* The size of the part was found to be the key characteristic in determining the level of difficulty in obtaining the part from the kit. Parts were categorized according to the following handling characteristics:

Minipart	The operator is able to carry multiple parts in one hand.
Small part	The operator is able to carry one part in each hand.
Medium part	One operator can carry one part per trip.
Large part	It takes two operators to move the part.
Extra-large part	It takes more than two operators and/or a hoist to move the part.

A representative MOST analysis was developed for each of these categories and stored in the database for use in developing standards.

2. *Verify the part number.* This activity takes place before the part is brought to the work area and ensures that the correct part number is used for assembly. A single suboperation was developed to cover all of the variations that exist in this activity.

3. *Unpack and recycle the packing material.* This activity takes place when the operator has found the right part needed for a specific operation. To maintain the surface finish of the part, it is protected in plastic bag or Bubble Wrap, depending upon its characteristics. The packaging material is either recycled or discarded. MOST analyses were developed to represent different-sized components.

4. *Position the part in structure.* This variable activity is influenced most by the size of the part and its alignment, which is determined from the blueprint or assembly instructions (including digital photographs of the part and the assembly and step-by-step method of its installation in the airplane).

5. *Hold the part in structure using temporary fasteners.* This variable activity depends on the type and number of clamping and holding devices required. The part may or may not have holes drilled at this stage. Some of the various fasteners and clamps used are Clecos, Wedgeloks, C-clamps, and Q-clamps. Standard data suboperations were developed for one occurrence of using each of these clamps and temporary fasteners, and results were stored in the database.

Top-down analysis was then performed on the next task, *drilling,* which is based on a number of variables such as the following:

1. Type of material, degree of thickness and hardness
2. Type of drill gun
3. Types of drill-jig
4. Diameter of hole(s) to be drilled
5. Tolerance range on the holes
6. Type of deburring tool required
7. Vacuuming the shavings

Statistical principles from the MOST system were used to minimize the number of suboperations needed to cover the range in variability from the simplest case of drilling to the most difficult type of drilling. Standards are developed by picking the appropriate category of drilling and applying a frequency to reflect the number of holes that need to be drilled.

A similar top-down analysis was performed for all of the remaining major assembly processes.

Each of the five process steps for assembly of structural parts includes various activities that differ from one part to another. This creates many combinations and choices for the person developing the labor standard. This could lead to inconsistencies in the application of standard data resulting in variations in labor standards. The MOST system uses the theory of *balancing time* and *occurrence frequency group* (OFG). In simplistic terms, this means that if a variable activity takes place infrequently, then the various possible methods in which this activity is performed can be averaged and represented by a single standard data suboperation. The number of times this activity is performed by an assembler each day and the length of the activity determine the precise number of suboperations needed to cover a variable activity. The system maintains the overall accuracy of labor standards as long as the labor standard is larger than the balancing time of the system.

This feature of the MOST system allowed us to combine various processes and use the average or weighted average of their time values. The data combining the various processes is called a *combined suboperation.* The prime example of this feature will be the process of holding a part in the structure with temporary fasteners. A separate analysis was developed for each type of fastener or clamp and filed in the database. Then we combined those various analyses into one standard data suboperation. This increased the consistency, as all the users were applying the same standard data to install a temporary fastener.

The same methodology was applied to all other tasks to account for all variations for drilling; installation of various fasteners; cleaning; application of sealer; installing harnesses and cables; splicing and wire terminations; installing tubing and hoses; and installing clamps, fittings, couplings, and so on.

Figure 5.10.1 shows an example of a time standard developed using the standard data approach.

IMPLEMENTATION OF CHANGES AND IMPROVEMENTS

The first Type I standards with the present system were developed in 1987. Since then, millions of standards have been developed for five military aircraft programs: F/A-18 Hornet, T-45 Goshawk, C-17 Globemaster III, F-15 Eagle, AV-8B Harrier. (See Figs. 5.10.2 to 5.10.6.) The current industrial engineering group maintains these standards and works on various other continuous process improvements, cost reduction, and quality initiatives. The IE group is also responsible for bringing new technology to the shop floor.

RESULTS AND FUTURE ACTIONS

The philosophy stating that “in order to manage, one must measure” is proven every day. Labor standards are a basis for managing a company’s manufacturing operations. How well these standards are maintained (and used) determines how productively manufacturing operations will be completed. Boeing is the world leader in aircraft production, and its use of industrial engineering tools to manage productivity has enhanced its ability to manufacture a high-quality product at a competitive price.

It is very important to keep track of all the methods changes that take place in an operation. A labor standard is good as long as it reflects current shop conditions, processes, and area layouts. In order to retain the integrity of a labor standard, all these changes must be accounted for. Maintaining accurate labor standards is a real test of the system. A database loaded with millions of labor standards should be responsive to your need to extract a standard, make a change, and file it back in the database.

Operation report—Combined report
The Boeing Company

Oper ID: 304215	Status: Private	DBName: ASY
Description: FORMER ASSY		
Model: 04	Part No: 123456XC56	Std. Type:1
Part Name: UPR M.L.	Oper No: 002000	OLC: ZX01
Dept No: 1174	Crew Size: 1	PCL: U
Spare Code:	Start A/C#: 535	Posting No: 9904
Part Type: LO	Part Size:	PPC: 1,000
Material Desc:		Use Code: 11
Material Spec:		
Req Type: P	Audit Date:	Worksheet ID: 63414
Run or Setup: RUN	Manual Allow: 15,000	Process Allow: 0.000
IE: CKVASY		Issue: 1
Create Date: 4/7/99		Effective Date: 4/20/99
Operator Instr:		
Applicator Instr:		

Step	Sub-op ID	Description	Special allowance	Freq	Hrs	Internal to
1	5756	CHECK & STAMP TIME	0.0000	1	0.01535	
2	5735	PREP	0.0000	1	0.02152	
3	5612	ASSEMBLE PART 'XC56'	0.0000	1	0.02609	
4	5611	ASSEMBLE PART 'XD67'	0.0000	4	0.03889	
5	5671	INSTALL PLATE 'PF23' WITH PINS	0.0000	1	0.02837	
6	5623	DRILL FIRST HOLE WITH HAND DRILL GUN	0.0000	3	0.05034	
7	5766	DRILL ADDT'L HOLE	0.0000	7	0.02151	
8	5671	INSTALL PLATE 'PF34'	0.0000	1	0.02837	
9	5611	ASSEMBLE 'MP01' ON STRUCTURE	0.0000	3	0.02917	
10	5623	DRILL HOLE WITH HAND DRILL GUN	0.0000	1	0.01678	
11	5766	DRILL ADDT'L HOLE	0.0000	5	0.01537	
12	5681	INSTALL 'MP02' IN FIXTURE	0.0000	1	0.02336	
13	5611	ASSEMBLE 'MP03'	0.0000	2	0.01945	
14	5621	DRILL HOLE	0.0000	1	0.01626	
15	5779	DRILL ADDT'L HOLE	0.0000	3	0.00822	
16	4192	REMOVE FIXTURE	0.0000	1	0.02038	
17	7309	PREPARE SEALER	0.0000	1	0.08203	
18	5129	SET-UP TOOLS	0.0000	2	0.02024	
19	5965	INSTALL FASTENER	0.0000	16	0.16624	
20	5611	ASSEMBLE MINI PART ON STRUCTURE WITH HAND	0.0000	1	0.00972	
21	5623	DRILL HOLE IN ALUMINUM	0.0000	2	0.03356	
22	5963	INSTALL FASTENER	0.0000	2	0.01729	
23	5919	INSTALL GROMMET	0.0000	1	0.01063	
24	5611	ASSEMBLE PART 'MP12'	0.0000	1	0.00972	
25	5621	DRILL HOLE	0.0000	2	0.03252	
26	4080	REMOVE TEMPORARY FASTENERS	0.0000	3	0.01047	
27	5953	IDENTIFY LABEL	0.0000	1	0.01774	
28	5947	TEAR DOWN TOOLS	0.0000	1	0.02650	

FIGURE 5.10.1 Example time standard.

Operation report—Combined report
The Boeing Company

Type of work	Elemental time	Allowance percent	Allowance time	Standard time
External manual	0.81609	15.000	0.12241	0.93850
Assigned internal	0.00000	15.000	0.00000	0.00000
Internal labor hours	0.00000	15.000	0.00000	0.00000
Process time	0.00000	0.000	0.00000	0.00000
Std. (hrs/cycle)	0.81609		0.12241	0.93850
	Pieces/cycle:	1.000		
	Cycle (hrs):	0.93850		
	Total labor (hrs):	0.93850		
	Pieces per hr @ 100%:	1.06553		

FIGURE 5.10.1 Example time standard. (*Continued*)

The first standards were developed for the current system over 10 years ago. Since then, most of the millions of aircraft operations have experienced numerous design and methods changes. These changes are reflected in the standards by adding or deleting from the list of standard data (method) steps in the operations or by changing the frequency applied to the steps. The standard data approach makes it possible to evaluate only the changed portion of the operation instead of restudying the entire operation. The need for a revision to a standard is normally triggered by the release of an engineering change or by the request of production management who have experienced changes in work methods or automation. When either of these conditions arises, industrial engineering evaluates the affected standard(s) to determine how it should be changed.

FIGURE 5.10.2 AV-8B Harrier.

FIGURE 5.10.3 C-17 Globemaster III.

FIGURE 5.10.4 F-15 Eagle.

CASE STUDY: LABOR STANDARDS FOR LONG-CYCLE JOBS IN THE AEROSPACE INDUSTRY

FIGURE 5.10.5 F/A-18 Hornet.

B
NAVY
206
T-45 Goshawk
McDONNELL DOUGLAS

FIGURE 5.10.6 T-45 Goshawk.

The emphasis on MIL-STD 1567A (which requires the application of accurate engineered standards) has been reduced, but the industrial engineering department continues to maintain standards because of their importance in managing a very complex manufacturing operation.

BIOGRAPHIES

Chandler Varma is industrial engineering manager at Military Aircraft & Missile Systems Division of The Boeing Company, in St. Louis, Missouri. He and his group have been actively involved in various process developments in the company and, most recently, in implementing the concepts of lean manufacturing and ISO-9000 certification. Varma has a B.S. in Mechanical Engineering and has been working as an industrial engineer for 11 years.

Joe May is a business development manager with H. B. Maynard and Company, Inc. He has assisted Maynard clients for 17 years, most recently by designing improvement programs and managing Maynard consultants in delivering results with those programs. May has a B.S. in Industrial Engineering from Purdue University in West Lafayette, Indiana.

CHAPTER 5.11

CASE STUDY: STAFFING A NEWSPAPER PRESSROOM OPERATION

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This case study discusses the development of staffing parameters for new presses and the eventual implementation of reduced staff on these new presses. The objective of the pressroom staffing study at *Toronto Star* was to determine the correct staffing for the efficient operation of the new presses at the Vaughan Press Center. The approach was to meet with union representatives, explain the procedures, and elicit their cooperation in the study. The management and union representatives were given an appreciation of the work measurement technique and, along with the consultant, reviewed each operation to determine the time required to complete it. Frequencies for each elemental task were also determined with union participation. The time and frequencies provided the basis for determining the staff requirements. These staffing requirements were presented to management and union for review. The union protested the findings of the staffing study. The result was arbitration of the findings and eventually a negotiated agreement between the parties.

BACKGROUND AND SITUATION ANALYSIS

The *Toronto Star* had recently purchased six new MAN Roland Colorman presses. These presses were installed in its newly constructed Vaughan Press Center in Vaughan, Ontario. The union is represented by the Graphic Communications International Union (GCIU). The existing contract allowed management to establish staffing on new or modified equipment. The union has the right to grieve the new staffing and submit the grievance to arbitration if both sides cannot agree on the recommended staffing.

New Equipment

Each of the new MAN Roland presses consists of 12 reel stands and 50 print couples. A *print couple* is defined as one plate cylinder, one blanket cylinder, and associated ink and water rollers. The 50 print couples allow the *Star* to have process color on 28 pages and spot color on 20 pages in straight mode (i.e., one-half of all pages could have some color). The 12 reel stands allow the *Star* to print 96 pages straight or 192 pages collect. The reel stands are capable of handling 50-inch-diameter newsprint rolls. Each of these 50-inch-diameter rolls is capable of producing approximately 31,500 impressions per roll. The rolls are delivered automatically to the correct reel stand by automated guided vehicles (AGVs). These rolls are located on the transfer table in the correct orientation (left or right, depending on which reel stand required the roll). The new presses are controlled at three computer consoles in the quiet room. These consoles control the color density on each page and section of the page, the cutoff on each web and page, the speed of the press, and registration of each couple (lateral and circumferential). Each quiet room is provided with an automatic drop station where a newspaper is dropped on command. These new presses have an automatic web-leading track. This track requires the press operator to place a *kite* on the roll and attach the end of the kite to the track. The kite is a triangular piece of plastic attached to the newsprint roll with approximately 20 strips of plastic tape. The track then feeds the web through the print couples all the way to the drag rollers in front of the formers. The web is then led manually (hand to hand) from the drag rollers through the compensators and/or angle bars to the former boards and ultimately to the folder.

Old Equipment

The six old Crabtree Vickers' presses were semiautomatic. They had automatic pasters, but the rolls were delivered by forklift. The color density and registration controls were on each unit, causing the press operators to walk from the folder, where they picked up the paper, to each unit. The cutoff and other folder controls (i.e., press speed) were on the folder—less distance, but the press operators are working in a dirty, noisy area. There was no quiet room on these presses. In order to correct registration, the press had to be shut down and the print couple moved manually at the unit. Whenever the press is shut down there is a greater chance of breaking a web. When one or more webs are lost, the press is shut down and must be rewebbed prior to starting the press, thus resulting in additional time. The newsprint rolls were 40-inch-diameter rolls, which required more frequent roll changes (approximately 20,000 impressions per roll). Because of equipment improvements, management felt that there should be a considerable reduction in staff on each press crew. These presses required the webs to be led manually (hand over hand) from the print couples through the former into the folder.

Contract Language

The old contract allowed for a maximum of 13 press operators on each press run. This staffing varied depending on the number of webs (reel stands) and print couples in operation. Union negotiations regarding the staffing requirements had resulted in impasse, and management was searching for a way to bring the contract to a successful conclusion by reducing staff on each press run. The union contended that the new presses required more workers because there were more print couples and more reel stands on the new presses. Because the union had filed a grievance, the *Toronto Star* temporarily kept the old staffing pending resolution of the grievance. The *Star* could have forced reduced staffing because of the wording in the contract, but rather than fight with the union over this right, the company allowed the maximum staffing of 13 for most press runs.

OBJECTIVES AND SCOPE

The objectives of this study were to achieve a reduction in staffing on all press runs without increasing the makeready time on any of these runs. The staff not required for the production runs would be utilized to form a press maintenance crew, resulting in no job losses for the press operators.

CASE STUDY: STAFFING A NEWSPAPER PRESSROOM OPERATION

Pressroom production staffing was broken down into two main categories: production and makeready. First the production staffing was determined. The procedures used will be discussed in detail later. The production staffing includes work to be performed in the reel room as well as on the press decks. This staffing can be broken into reel-room staffing and press-level staffing. This study reviewed each area separately and combined the reel-room work with the press-level work in order to get the best workload balance for the crew and achieve the overall objective of reduced staffing. The *Star* press operators have the same classifications whether they work in the reel room or on the press decks; therefore, combining reel-room and press-level work was not a problem.

Once the production staffing has been determined, the makeready tasks are reviewed and the time requirements are established. The amount of time required for makeready is based on the production staffing. The makeready required time was calculated by dividing the total makeready hours by the required production staff.

ORGANIZATION OF THE PROJECT

Management Involvement

Meetings were held with all management personnel to explain the scope and procedures that were used in the development of staffing tables for the new presses. There was also discussion about how to introduce the project to the union. The best way to perform this type of study was with the union support. Information gained from discussions with the supervisors was used to determine the best approach for presenting the project to the union bargaining committee.

Union Involvement

Meetings were held with the union bargaining committee to explain the project. After the union committee had a complete understanding of the study, they were asked to participate by providing members to work with the consultant and management to determine the work content and staffing requirements. There was considerable reluctance on the part of the union to participate in the study. It was explained that it would be to their benefit to participate and have input rather than waiting until the project was completed and having to argue their points in front of an arbitrator. The union was told that the study would go on whether they participated or not. After weighing the pros and cons, the union agreed to become part of the study. The project team consisted of the consultant, the pressroom manager, and one union representative from each shift.

After all team members (union and management) were identified, they were given appreciation training in the MOST® work measurement system. The idea was not to make these members MOST applicators, but to enable them to read and understand the MOST analyses. MOST was chosen because it was designed to measure semirepetitive motion patterns such as those in the pressroom. MOST yields accurate and consistent standards that are fair and credible. It has been used in this industry many times, including in several cases involving arbitration.

The production operations on the night shift were the first operations observed. Before the observations began, meetings were held with the entire union "chapel" working nights. (In the newspaper industry, *chapel meetings* refer to local union meetings.) Similar meetings were also held for the union chapels on day and lobster shifts. These meetings provided a means to introduce the consultant and project team, describe the approach and techniques to be used, and inform the membership that there would be union members participating in the study. If the membership had any questions, then the union participants would answer them or refer them to someone who could.

As the study progressed, weekly meetings were held with management to discuss the progress, any problems encountered, and the plan for the following week. These meetings consisted of the consultant, pressroom manager, production manager, director of production, and the director of industrial relations.

Meetings were also held with the union bargaining committee on a regular basis to review all data developed to date. This review provided the union an opportunity to discuss the methods and standards for each operation. The goal was to get union agreement with the methods and standards.

PROCEDURE AND APPLICATION TOOLS

Methods Review and Agreement

The reel room was observed first, then the press level, and finally makeready tasks. As each task was observed, the methods were reviewed with all project team members. After there was agreement on the methods, the consultant performed the MOST analysis for each task. The MOST analyses and resultant task times were reviewed with the project team to provide the opportunity for consensus from all team members on the method and time requirements for each task. If questions remained regarding either the time requirement or method, the task was reviewed again until agreement was reached. Once agreement was reached, the team presented its findings to both management and union personnel. This practice ensured that the union and management were fully aware of all of the time measurements and had signed off prior to going into the next area. As stated earlier, the press production operation is broken down into two main categories: press production and press makeready.

Press Production

The primary tasks to be completed during press production are to prepare and load newsprint rolls, make adjustments to the press to maintain quality, change plates (edition change), and repair web breaks as they occur. Summaries of the required work activities and the work measurement times for press production are shown in Table 5.11.1. A detailed MOST analysis for each activity listed was provided to management and union officials.

TABLE 5.11.1 Press Production Work Activities

	Code[a]	Description	Per[b]	TMUs[c]	Std min[d]
1	RR-7	Change roll during production	Roll	12,490	8.62
2	F-18	Troubleshoot during run	Web	5,033	3.47
3	PL-15	Adjust color	Couple	2,637	1.82
4	PL-16	Adjust black	Couple	1,800	1.24
5	PL-22	Troubleshoot ink and water problems	Unit	3,216	2.22
6	PL-21	Complete press report	Shift	8,380	5.78
7	RR-10	Reweb press due to web break	Occur	38,650	26.66
8	PL-11	Change plates	Couple	14,624	10.09
9	PL-19	Check web tensions	Web	1,650	1.14
10	F-14	Adjust fold rollers	Adjust	2,150	1.48
11	F-15	Adjust nips	Adjust	2,450	1.69
12	F-19	Adjust heads and tails	Web	1,420	0.98

[a] Code = The MOST analysis code number.
[b] Per = Unit of measure.
[c] TMU = Measured time (100,000 TMU = 1 hour).
[d] Std min = TMUs/1667 + 15% (9200 /1667 + 15% = 5.52 + .83 = 6.35).

In order to calculate the total time requirement for press production, the frequency for each task shown in Table 5.11.1 must be determined. During production, press operators are required to monitor and adjust the press to maintain the quality of the product. The best way to determine the frequency for each task was to calculate how many times that task would need to occur each hour. Based on the project teams' observations, the press operators pulled copies approximately every 6 minutes. Each page of these copies was inspected for quality. During the period of observation, an average of 50 percent of the pages inspected required a quality adjustment. The number and type of run adjustments are based on the number of reel stands and the quantity and type of print couples in operation. The frequencies are based on the worst-case assumption that all color couples will be utilized first. The MAN Roland presses have 12 reel stands and 50 print couples. To produce the color photographs seen on page one of your newspaper, a four-color process is used. Each photo is broken down into its four primary colors: cyan, magenta, yellow, and black. Each print couple will imprint one of these colors to the web. The worst-case scenario, then, would be to assume that the first webs would print process color on both sides, thus using eight print couples. Eight print couples are required because four couples are required to print process color on one side of the web and four print couples are required to print process color on the opposite side of the web. This allowance of eight couples for one web is really the worst-case example because the normal procedure would be the run process color on one side of the web and black only on the opposite side. Thus, only five print couples would be utilized instead of eight. The adjustment of the heads and tails of each page is allowed continuously during the run—up to 60 times per hour based on 12 reel stands. Obviously, after initial start-up, the only changes to the heads and tails occur after a paster is fired and the new roll is running.

Also during production, the reel room must change rolls to maintain output. The frequency of roll changes is dependent on the number of impressions per roll and the speed of the press. The *Star* uses 50-inch-diameter rolls containing an average of 31,550 impressions per roll. The frequencies for run adjustments are shown in Table 5.11.2.

The frequencies for roll changes are based on press speed and the net impressions per roll. The press speed is limited by the folder capacity. According to the specifications from MAN Roland, the folder capacity is 37,500 cylinder revolutions per hour, or 75,000 impressions per hour. The top sustained printing speed is 35,000 cylinder revolutions per hour (70,000 impressions per hour) when running 28- to 30-pound paper. The folder capacity peaks between five and eight rolls (40- to 64-page newspaper), and the press runs slower up to five rolls and after eight rolls. As discussed earlier, the average net impressions per roll experienced at the Vaughan Press Center has been 31,550. The frequencies for roll changes are shown in Table 5.11.3.

The standard times are calculated by multiplying the standard minutes from Table 5.11.1 by the frequencies from Tables 5.11.2 and 5.11.3. The standard times for run adjustments are shown in Table 5.11.4.

TABLE 5.11.2 Frequencies for Run Adjustment

	Reel stands	1	2	3	4	5	6	7	8	9	10	11	12
	Color couples	6	12	15	18	21	22	23	24	25	26	26	26
	Black couples	2	4	6	8	10	12	14	16	18	20	22	24
Code	Run adjustment												
F-18	Troubleshoot during run	1	2	3	4	5	6	7	8	9	10	11	12
PL-15	Adjust color	6	12	15	18	21	22	23	24	25	26	26	26
PL-16	Adjust black	2	4	6	8	10	12	14	16	18	20	22	24
PL-22	Troubleshoot ink and water	5	5	5	5	10	10	10	10	15	15	15	15
PL-19	Check web tensions	1	2	3	4	5	6	7	8	9	10	11	12
F-14	Adjust fold rollers	1	1	1	1	1	1	1	1	1	1	1	1
F-15	Adjust nips	1	1	1	1	1	1	1	1	1	1	1	1
PL-21	Complete press report	1	1	1	1	1	1	1	1	1	1	1	1
F-19	Adjust heads and tails	5	10	15	20	25	30	35	40	45	50	55	60

TABLE 5.11.3 Roll Changes per Hour: Net Impressions per Roll = 31,550

	Reel stands											
Press speed	1	2	3	4	5	6	7	8	9	10	11	12
70,000					11.1	13.3	15.5	17.7				
65,000			6.2	8.2	10.3	12.4	14.4	16.5	18.5	20.6		
60,000		3.8	5.7	7.6	9.5	11.4	13.3	15.2	17.1	19.0	20.9	22.8
55,000	1.7	3.5	5.2	7.0	8.7	10.5	12.2	13.9	15.7	17.4	19.2	20.9
50,000	1.6	3.2	4.8	6.3	7.9	9.5	11.1	12.7	14.3	15.8	17.4	19.0

The standard times for roll changes are determined by multiplying the standard minutes from Table 5.11.1 by the frequencies for roll change from Table 5.11.3. Table 5.11.5 shows the standard times for roll changes.

The crew size is determined by dividing the total standard minutes by 60 minutes per hour. The recommended crew for the pressroom is determined by adding the standard minutes of work for each area (i.e., press level and reel room) and dividing the total standard minutes by 60 minutes per hour. Table 5.11.6 shows the recommended crew.

A minimum crew of five people is needed to reweb the press after a web break. The time to reweb the press is calculated on the use of five people. These five people are located as follows: one person in the reel room, one person at the midlevel deck, one person at the drag rollers, one person at the former, and one person to feed the web over and around various roller and bars.

Press Makeready

Press makeready includes all tasks necessary to set up the press to start production for the next run. Makeready begins with stirring ink and ends with making prerun adjustments. The sequence of tasks for makeready is as follows: Stir ink; clean web detectors; load rolls; make up kites; lead sheets; set folder; plate up; start up; run 800 copies; make prerun adjustments; restart and adjust. All makeready tasks were observed by the project team. A summary of the makeready activities was presented to management and the union committee for review. Upon acceptance, MOST analyses were completed, just as was done during the production measurement process. These task times were reviewed by management and union committees. Again, if any questions arose concerning the method description or standard time, the tasks were observed again until all were satisfied with the measured time.

TABLE 5.11.4 Standard Times for Run Adjustments

	Reel stands	1	2	3	4	5	6	7	8	9	10	11	12
	Color couples	6	12	15	18	21	22	23	24	25	26	26	26
	Black couples	2	4	6	8	10	12	14	16	18	20	22	24
Code	Run adjustment												
F-18	Troubleshoot during run	4.2	8.4	12.7	16.9	21.1	25.3	29.5	33.8	38.0	42.2	46.4	50.6
PL-15	Adjust color	10.9	21.8	27.3	32.8	38.2	40.0	41.9	43.7	45.5	47.3	47.3	47.3
PL-16	Adjust black	2.5	5.0	7.4	9.9	12.4	14.9	17.4	19.8	22.3	24.8	27.3	29.8
PL-22	Troubleshoot ink and water	11.1	11.1	11.1	11.1	22.2	22.2	22.2	22.2	33.3	33.3	33.3	33.3
PL-19	Check web tensions	1.1	2.3	3.4	4.6	5.7	6.8	8.0	9.1	10.3	11.4	12.5	13.7
F-14	Adjust fold rollers	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5
F-15	Adjust nips	1.7	1.7	1.7	1.7	1.7	1.7	1.7	1.7	1.7	1.7	1.7	1.7
PL-21	Complete press report	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0
F-19	Adjust heads and tails	4.9	9.8	14.7	19.6	24.5	29.4	34.3	39.2	44.1	49.0	53.9	58.8
	Total std min per hour	38.9	62.6	80.8	99.0	128.3	142.8	157.4	171.9	197.6	212.2	224.9	237.6

TABLE 5.11.5 Standard Times for Roll Change

	Reel stands											
Press speed	1	2	3	4	5	6	7	8	9	10	11	12
70,000					95.6	114.8	133.9	153.0				
65,000			53.3	71.0	88.8	106.6	124.3	142.1	159.8	177.6		
60,000		32.8	49.2	65.6	82.0	98.4	114.8	131.1	147.5	163.9	180.3	196.7
55,000	15.0	30.1	45.1	60.1	75.1	90.2	105.2	120.2	135.2	150.3	165.3	180.3
50,000	13.7	27.3	41.0	54.6	68.3	82.0	95.6	109.3	122.9	136.6	150.3	163.9

In order to calculate the makeready time requirement, the frequencies for each task must be determined. The frequency for each task varies based on the number of reel stands and print couples in operation. To determine the frequency for changing roll size from full to half or three-quarter rolls it was assumed that, at most, every other roll would change. In the development of the makeready standard times, a maximum frequency (or worst-case scenario) was used. All frequencies are based on observations and discussions with management and hourly employees to establish the worst-case assumptions.

The standard minutes for makeready are calculated by multiplying the standard minutes for each task by the frequency for that task. The makeready standard minutes are shown in Table 5.11.7.

Table 5.11.8 shows the allowed makeready hours based on the recommended crew size.

IMPLEMENTATION OF CHANGES AND IMPROVEMENTS

As the study was proceeding, the company and union were continuing the negotiations to try to reach a settlement. Upon completion of the study, the conclusions were reviewed with management and union personnel. The recommended staffing of eight people maximum per press run was considerably less than the union expected. The bargaining committee refused to believe that eight people could handle the press with 12 reel stands and 50 couples in operation. The entire process of determining the eight-person staff requirement was reviewed with the bargaining committee. All task times and frequencies were reviewed. The committee was asked if there were any tasks that were missed or any work that needed to be added. The union did not find any work or tasks that had been omitted. However, when asked to agree to the staffing recommendation, the union refused.

TABLE 5.11.6 Total Press Crew Staffing

	Footprints											
Press speed	1	2	3	4	5	6	7	8	9	10	11	12
70,000					5	5	5	6				
65,000			5	5	5	5	5	6	6	7		
60,000		5	5	5	5	5	5	6	6	7	7	8
55,000	5	5	5	5	5	5	5	5	6	7	7	7
50,000	5	5	5	5	5	5	5	5	6	6	7	7
Recommended press crew												
	Footprints											
	1	2	3	4	5	6	7	8	9	10	11	12
Crew	5	5	5	5	5	5	6	6	7	7	8	8

TABLE 5.11.7 Makeready Standard Minutes

Code	Description	1	2	3	4	5	6	7	8	9	10	11	12
	Reel stands	1	2	3	4	5	6	7	8	9	10	11	12
	Color couples	6	12	15	18	21	22	23	24	25	26	26	26
	Black couples	2	4	6	8	10	12	14	16	18	20	22	24
	Press level												
PL-1	Stir ink	8.4	16.8	21.0	25.2	29.4	30.7	32.1	33.5	34.9	36.3	36.3	36.3
PL-2	Move fountain for ½ roll	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5
PL-3	Replace fountain for contamination	5.1	5.1	5.1	5.1	5.1	5.1	5.1	5.1	5.1	5.1	5.1	5.1
PL-4	Check color imposition list	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4
PL-5	Set ink levels at console	2.0	4.0	5.2	6.5	7.7	8.4	9.2	9.9	10.7	11.4	11.9	12.4
PL-6	Check unit function lights	0.3	0.7	1.0	1.3	1.7	2.0	2.3	2.7	3.0	3.4	3.7	4.0
PL-7	Lead kite from reel room to top of	24.0	47.9	71.9	95.9	119.9	143.8	167.8	191.8	215.8	239.7	263.7	287.7
PL-8	Lead kite from top of chain to fold	20.9	41.7	62.6	83.5	104.3	125.2	146.1	166.9	187.8	208.7	229.6	250.4
PL-9	Web up from former to delivery	30.1	30.1	30.1	30.1	60.3	60.3	60.3	60.3	90.4	90.4	90.4	90.4
PL-10	Get plate cart to press	14.8	14.8	14.8	14.8	14.8	14.8	14.8	14.8	14.8	14.8	14.8	14.8
PL-11	Plate up	80.7	161.4	211.9	262.3	312.7	343.0	373.3	403.5	433.8	464.1	484.3	504.4
PL-12	Engage/disengage slitters	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8
PL-13	Check ink blade adjustment	5.4	10.8	14.2	17.6	21.0	23.0	25.0	27.0	29.1	31.1	32.5	33.8
PL-17	Initiate makeready	2.3	2.3	2.3	2.3	2.3	2.3	2.3	2.3	2.3	2.3	2.3	2.3
PL-18	Check strike and oscillation	1.6	1.6	1.6	1.6	1.6	1.6	1.6	1.6	1.6	1.6	1.6	1.6
PL-19	Check web tension	1.1	2.3	3.4	4.6	5.7	6.8	8.0	9.1	10.2	11.4	12.5	13.7
PL-20	Clean web detectors	6.0	6.0	6.0	6.0	6.0	6.0	6.0	6.0	6.0	6.0	6.0	6.0
PL-23	Change angle bars	8.0	8.0	8.0	8.0	8.0	8.0	8.0	8.0	8.0	8.0	8.0	8.0
	Folder												
F-1	Clean former pans	2.6	2.6	2.6	2.6	2.6	2.6	2.6	2.6	2.6	2.6	2.6	2.6
F-2	Clean guide rollers	2.6	2.6	2.6	2.6	2.6	2.6	2.6	2.6	2.6	2.6	2.6	2.6
F-3	Clean angle bars	2.5	2.5	2.5	2.5	2.5	2.5	2.5	2.5	2.5	2.5	2.5	2.5
F-4	Make crew assignment	5.1	5.1	5.1	5.1	5.1	5.1	5.1	5.1	5.1	5.1	5.1	5.1
F-5	Clean folder fingers	8.4	8.4	8.4	8.4	8.4	8.4	8.4	8.4	8.4	8.4	8.4	8.4
F-6	Change cutting rubbers	9.2	9.2	9.2	9.2	9.2	9.2	9.2	9.2	9.2	9.2	9.2	9.2
F-7	Set up ferag	0.7	0.7	0.7	0.7	0.7	0.7	0.7	0.7	0.7	0.7	0.7	0.7
F-8	Set delivery height	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5
F-9	Set expansion bands	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8
F-10	Set infeed tensions	0.3	0.6	0.9	1.2	1.5	1.8	2.1	2.4	2.7	3.0	3.3	3.6
F-11	Check with reel room for start-up	1.4	1.4	1.4	1.4	1.4	1.4	1.4	1.4	1.4	1.4	1.4	1.4
F-12	Put press in thread mode	1.4	1.4	1.4	1.4	1.4	1.4	1.4	1.4	1.4	1.4	1.4	1.4
F-13	Set trolly pressure	1.4	1.4	1.4	1.4	1.4	1.4	1.4	1.4	1.4	1.4	1.4	1.4
F-14	Set fold rollers	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5
F-15	Set nips	3.4	3.4	3.4	3.4	3.4	3.4	3.4	3.4	3.4	3.4	3.4	3.4
F-16	Set former (sidelay and nose)	1.1	1.1	1.1	1.1	1.1	1.1	1.1	1.1	1.1	1.1	1.1	1.1
F-17	Change straight to collect												
	Reel room												
RR-8	Change roll size during makeready	28.1	28.1	28.1	28.1	56.3	56.3	56.3	56.3	84.4	84.4	84.4	84.4
RR-9	Complete roll report	4.4	4.4	4.4	4.4	4.4	4.4	4.4	4.4	4.4	4.4	4.4	4.4
RR-11	Move spider arms for new roll size	2.5	2.5	2.5	2.5	2.5	2.5	2.5	2.5	2.5	2.5	2.5	2.5
	Prerun adjustments												
PL-15	Adjust color and register at console	28.5	57.0	71.2	85.4	99.7	104.4	109.2	113.9	118.7	123.4	123.4	123.4
PL-16	Adjust black	7.2	14.3	21.5	28.7	35.9	43.0	50.2	57.4	64.6	71.7	78.9	86.1
F-19	Adjust heads and tails	6.3	12.7	19.0	25.4	31.7	38.1	44.4	50.8	57.1	63.5	69.8	76.2
	Total makeready std min	332.5	517.6	651.2	784.8	976.8	1076	1175	1275	1432	1532	1614	1696

TABLE 5.11.8 Makeready Hours Based on Recommended Crew Size

	Reel stands											
	1	2	3	4	5	6	7	8	9	10	11	12
Allowed MR std mins	332	518	651	785	988	1087	1187	1286	1455	1554	1636	1718
Crew size	5	5	5	5	5	5	6	6	7	7	8	8
MR hours	1.11	1.73	2.17	2.62	3.29	3.62	3.30	3.57	3.46	3.70	3.41	3.58

The bargaining committee continued to meet with management to reach settlement on the staffing provisions of the new contract. The company had earlier proposed 10 people as maximum staffing for 12 reel stands. The union bargaining committee asked if the company would continue to offer the 10-person maximum. The company agreed to keep the 10-person offer on the table, and the bargaining committee agreed to bring it before the rank and file for a ratification vote. The grievance procedure was also proceeding to arbitration. On the evening before the arbitration was to begin, the rank and file voted to turn down the contract proposal for a 10-person maximum. The rank and file insisted on a minimum of 13 people per press run. It did not matter what union leadership or team members said. The union and company then proceeded to arbitration.

Arbitration

It should be noted that arbitrations in Canada are slightly different than in the United States. In Canada, a tripartite panel normally hears the case. One member of the arbitration panel is picked by the union, another by the company, and the third by procedures similar to those used in the United States, in which 10 candidates are chosen at random and each party strikes names from the list until only one is left. This person becomes the third and highest-ranking panel member (the arbitrator).

The arbitration began the day after the ratification vote. The union, having initiated the grievance, was obligated to present its side first. It was apparent to all observers that the union leadership had assumed that the rank and file would ratify the new contract. The union was not prepared to open the arbitration. The union consul asked that the arbitration panel allow the company to present its case first, with the provision that it could later present rebuttal to the union case if necessary. The arbitrator allowed that, although highly irregular, the arbitration could begin if the company agreed to this. The company presented the findings of the staffing study. The consultant explained the study. The arbitration panel was walked through every step of the study and given an overview of the work measurement technique. The study's final report was used to present the work content and the staff requirements. During the break, the arbitration panel was taken on a walk-through of the operation that allowed them to see firsthand the entire pressroom operation. Each step in the study was reviewed during the walk-through. The arbitration panel had the opportunity to talk with press operators as they observed the operations. These conversations in combination with the study provided the arbitration panel with a thorough understanding of the daily newspaper production process.

Upon completion of the consultant's testimony, the company called the pressroom manager to testify. The pressroom manager was one of the team members on the staffing project. He testified regarding the procedures followed and the amount of cooperation provided by the union. He also testified that the union was given every opportunity to refute any findings during the course of the study.

Collective Bargaining

Because the union could not refute any of the study's findings or the staffing conclusions, the bargaining committee asked for additional bargaining sessions. The company readily agreed.

The company held to its original offer: The maximum staffing would be 10 people, and displaced press operators would make up the maintenance crew. During this time in 1994, there were approximately 45 press runs per week. The staffing offer meant that there would be at least 135 press maintenance shifts available for the displaced press operators.

The bargaining committee understood that if they did not strongly support the company offer to the rank and file, the arbitration panel would very likely rule that eight people was the maximum staffing required. The bargaining committee called for another vote, and the contract was ratified by a vote of 87 to 40. *Star* publisher John Honderich was quoted as saying he was "pleased with the agreement, particularly in view of problems associated with introducing new technology into workplaces." Further, said Honderich, "The fact that the newspaper and union were able to reach an agreement that both sides can accept is a great achievement. Ultimately, it also reflects a dedication by the employees to the economic well-being of the *Star.*"

Brian Fletcher, union president, said, "I have mixed feelings, but I think the deal we have is the most responsible way to go."

The union had complained that lack of proper maintenance was leading to frequent breaks in press runs and delays in printing and delivery of the newspaper. In addition, the union and management agreed that staffing and overtime would not be a bargaining issue in the next contract.

RESULTS AND FUTURE ACTIONS

The company was able to get much-needed maintenance and cleaning of the presses performed in a timely manner. This maintenance can now be scheduled and planned. The next step for the company was to perform a similar study in the maintenance area, which was conducted in 1997 using the same consultants. When the union was asked to participate in the maintenance study, it flatly refused. Union members who had participated in the original study were shunned for the first year after the contract agreement. They did not want to go through that stigma again.

The actual savings accrued because the company did not have to hire additional press operators to perform the maintenance tasks. Total savings amounted to approximately 40 people. The maintenance study supported the need for 40 press maintenance people. However, the work requirement for these people increased by 40 percent.

The reduction in staff resulted in several problems. For example, the presses were occasionally late in finishing the run for the first several months, and the union waited to see whether the company would add extra press operators. The company refused to do so, and the problem eventually disappeared.

BIOGRAPHY

Jack Ryan is a management consultant based in Williamsburg, Virginia. He graduated from Youngstown State University in Youngstown, Ohio, with a B.S. degree. He has over 30 years of productivity management experience. Over 16 years have been spent consulting with clients and working with them on the installation of industrial engineering services. He has worked with over 80 clients, several of which are in the printing business (Treasure Chest Advertising, *Baltimore Sun, Newsday, Toronto Star,* Philadelphia Newspapers Inc., etc.). These projects have been associated with work measurement, methods engineering, standard data, incentives, and staffing tables. Ryan has held positions ranging from industrial engineer to vice president of operations. He spent 11 years at H. B. Maynard and Company before founding his own firm.

SECTION 6

ERGONOMICS AND SAFETY

CHAPTER 6.1

ERGONOMIC INFORMATION RESOURCES

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Successful application of industrial ergonomics requires an understanding of human capacity, workplace design, musculoskeletal disorders, and occupational risk factors. Such information may not be readily available to nonspecialists charged with the responsibility of initiating ergonomic intervention in the workplace. The purpose of this chapter is to provide several sources of ergonomics information that an industrial engineer can refer to. These resources can be divided into three main categories: print, human/institutional, and electronic. The benefits and potential uses of each resource are described in detail.

INTRODUCTION

When attempting to ergonomically analyze, evaluate, and redesign the workplace, the most valuable tool at an engineer's disposal is access to information. Ergonomics information in particular can provide the engineer with appropriate procedures for identifying potential hazards, quantifying specific risk factors, and developing feasible solutions for those jobs associated with work-related musculoskeletal disorders (WRMSDs). This information can also yield design specifications that maximize human comfort or performance. The purpose of this chapter is to supply the engineer with various resources for ergonomics information. These resources can fall into one of the three following categories: print, human/institutional, and electronic. The list of reference sources to follow is not exhaustive. These materials will, however, provide the nonspecialist with a starting point to develop the basic tools necessary when conducting rudimentary ergonomic evaluations.

The information provided by the resources listed in this chapter will be based on one of three types of ergonomics research, as defined by Sanders and McCormick (1993): descriptive, experimental, and evaluative.

Descriptive Research

These resources document collected data used by ergonomists in making many workplace design decisions. Such resources may include data tables that characterize a population by specific physical characteristics, performance characteristics, subjective responses (i.e., preference), and physiological indices (e.g., heart rate). Descriptive resources can also provide information that assesses the magnitude and scope of a particular ergonomics-related problem (such as the incidence and severity of cumulative trauma disorders in industry).

Experimental Research

These resources document research that tests the effects of some variable (e.g., treatment) on human performance, behavior, or physiological response. Such research centers on the relative differences in human performance/response under various treatment conditions. The information found in experimental resources can be based on laboratory research or on data collected from field expeditions to actual industrial operations. The ergonomics professional can use information found in experimental resources to justify changes he or she may propose for the working environment. Experimental resources may also contain analytical tools useful for hazard evaluation and ergonomic intervention.

Evaluative Research

These resources seek to describe the performance and behavior of people using the system (e.g., workstation) or product (e.g., toothbrush). In evaluative research, the effect of something (system or product) on human performance, behavior, or physiological response is the primary focus. Most good evaluative research is conducted under conditions representative of those in which the system or product being tested will actually be used. In addition, the subjects selected for good evaluative research are representative of the ultimate user population for the particular system or product. Evaluative resources can include case studies, which document the specific procedures involved in the ergonomic modifications of a workstation, along with the benefits incurred from such an intervention. The ergonomics professional can use evaluative resources to assist in developing his or her own creative and effective ideas for improving a particular work environment from an ergonomics perspective.

The reader should note that a single resource (print, human/institutional, and electronic) may possess information that is related to more than one category (descriptive, experimental, and evaluative) of ergonomics research.

Print Resources

This section includes peer review journal publications, books, and government publications that cover various ergonomics-related topics ranging from the latest scientific research to case studies. A brief description of contents will be included with each listing.

Peer Review Journal Publications. These references can be found in public or university libraries.

Ergonomics—The flagship journal of the human factors community. This journal focuses primarily on descriptive and experimental research in human factors.

Applied Ergonomics—This journal showcases primarily evaluative research focusing on jobs people do and things people use. However, some descriptive research can be found in this publication as well. Case studies documenting the benefits of human factors intervention are often found in this publication.

ERGONOMIC INFORMATION RESOURCES

Human Factors—The official publication of the Human Factors and Ergonomic Society, this journal places most of its emphasis on experimental and evaluative research dealing with human perception and cognition.

International Journal of Industrial Ergonomics—This journal presents experimental and evaluative research directed at reducing accidents, injuries, and illnesses encountered by people doing work.

International Journal of Human-Computer Interaction—This journal documents evaluative research focusing on improving human usage and satisfaction with computer hardware, software, and computer-related tasks.

Journal of Human Ergology—Descriptive, experimental, and evaluative research by human factors specialists in Japan is the focus of this journal.

International Journal of Man-Machine Systems—This journal presents evaluative research dealing with human factors issues found in production and manufacturing environments.

Government Publications. Many print sources can be ordered from the two U.S. government agencies that have specific departments that address human factors–related issues:

Occupational Safety and Health Administration (OSHA)

National Institute for Occupational Safety and Health (NIOSH)
OSHA Publications

Ergonomics: the Study of Work—general introductory booklet documenting basic ergonomic principles for safe working conditions

Working Safety with Video Display Terminals—makes recommendations for safe human-computer interaction

Ergonomic Recommendations for Meatpacking Plants—documents ergonomic management program specifications for the meat-packing industry

Ergonomic Recommendations for General Industry—documents ergonomic management program specifications for general industry

OSHA Workstation Improvement Plan—documents procedures followed by OSHA engineers as they try to improve (from a human factors perspective) over 400 visual display terminal workstations in the Department of Labor building in Washington, D.C.

Order from: The Office of Ergonomic Support, Room N3636, 200 Constitution Avenue, Washington, D.C. 20210/(202) 693-2333.
NIOSH Publications

Work Practices Guide to Manual Lifting—documents the NIOSH Lifting Equation, which allows the user to calculate the amount of weight that is safe to lift given certain task conditions (experimental research)

Participatory Ergonomic Interventions in Meat Packing Plants—presents evaluative research that documents ergonomic intervention strategies effectively applied to operations found in the meat-packing industry

NIOSH Health Hazard Evaluations (HHE)—documents risk factors for ergonomics-related problems found in various industrial operations (and the steps taken to address such problems)

Fax requests to: Publications Dissemination, NIOSH, 4676 Columbia Parkway, Cincinnati, OH 45226/(513) 533-8573.

The International Organization for Standardization (ISO). This organization sets the various workplace standards (codes) for the European Community (EC).

ISO-NORM 9241 (*Parts 10–17*) *Software Ergonomic Evaluation*—This standard specifies the generic characteristics that software applications should possess to be user friendly. This standard also provides engineers with the means to identify potential weak points (human factor–related) in software prototypes.

Books. The following is a list of books that cover various aspects of ergonomics:

Ergonomics for Beginners: Quick Reference Guide, Taylor & Francis, Washington DC, 1993.

Creating the Ergonomically Sound Work Place, Jossey-Bass, San Francisco, 1994.

Applied Ergonomics Handbook, Lewis, Boca Raton, FL, 1991.

Cumulative Trauma Disorders, Taylor & Francis, New York, 1988.

Introduction to Ergonomics, McGraw-Hill, New York, 1995.

Evaluation of Work: Practical Ergonomics Methodology, Taylor & Francis, New York, 1995.

Human Factors in Engineering and Design, McGraw-Hill, New York, 1992.

Ergonomics: How to Design for Ease and Efficiency, Prentice Hall, Englewood Cliffs, NJ, 1992.

Work Design: Industrial Ergonomics, Publishing Horizons, Columbus, OH, 1995.

Ergonomic Design for People at Work, Vol. I, Van Nostrand Reinhold, New York, 1989.

Ergonomic Design for People at Work, Vol. II, Van Nostrand Reinhold, New York, 1989.

Musculoskeletal Disorders in the Work Place, Mosby, St. Louis, MO, 1997.

Work Related Musculoskeletal Disorders, Taylor & Francis, New York, 1995.

Occupational Biomechanics, John Wiley & Sons, New York, 1999.

Anthropometric Methods: Designing to Fit the Human Body, Human Factors and Ergonomics Society, Santa Monica, CA, 1995.

Human Factors Design Guide for Acquisition of Commercial Off-the-Shelf Subsystems, NonDevelopmental Systems, The FAA Technical Center, 1996 CD-ROM available at www.tc.faa.gov/hfbranch/hfdg/indesx.html#overview.

Human/Institutional Resources

This section lists training facilities where one can receive ergonomics instructional courses. Although this listing contains only ergonomics instruction offered by public institutions, it should be noted that some insurance companies and industrial consulting groups offer these services as well.

NIOSH: Division of Training and Manpower Development, 4676 Columbia Parkway, Cincinnati, OH 45226. (513) 533-8417.

Deep South Center for Occupational Health and Safety, University of Alabama, School of Public Health, Birmingham, AL 35294. (205) 934-7178.

Northern California Center for Occupational and Environmental Health, 1301 South 46th Street, Building 102, Richmond, CA 94804. Contact: Barbara Plog (510) 231-5647.

University of Southern California, Institute of Safety and Systems Management, Room 102, Los Angeles, CA 90089. Contact: Ramina Cayuela (213) 740-3998.

University of Michigan, Center for Ergonomics, 1205 Beal Avenue, Ann Arbor, MI 48109. Contact: Randy Raboutn or Patricia Cottrell (313) 763-0567.

University of Cincinnati, Department of Environmental Health, PO Box 670056, Cincinnati, OH 45267. Contact: Amit Bwattacharva (513) 558-1731.

North Carolina State University, Department of Industrial Engineering, Box 7906, North Carolina State University, Raleigh, NC 27695. Contact: Dr. Gary Mirka (919) 515-6399.

University of Pittsburgh, Department of Industrial Engineering, 1048 Benedum Hall, Pittsburgh, PA 15261. Contact: Dr. Mark Redfern (412) 647-7923.

Harvard School of Public Health, Office of Continuing Education, 677 Huntington Avenue, Boston, MA 02115. Contact: Kathryn Lord (617) 432-3518.

University of Utah, 3209 Merrell Engineering Building, Department of Mechanical Engineering, Salt Lake City, UT 84112. Contact: Dr. Donald Bloswick (801) 581-4163.

National Safety Council, 1121 Spring Lake Drive, Itasca, IL 60143. Contact: Bonnie Piddington (800) 581-4163.

University of Houston, School of Public Health, Department of Industrial Engineering, 4800 Calhoun Street, Houston, TX 77204. Contact: Lawrence Schultz (713) 743-4196.

Ohio State University, Department of Industrial and Systems Engineering, 1971 Neil Avenue, Columbus, OH 43210. Contact: Dr. William Marras (614) 292-7852.

Engineering Department, University of Nebraska-Lincoln, 175 Nebraska Hall, Lincoln, NE 68588. Contact: Dr. Michael Riley (402) 472-3495.

Johns Hopkins Educational Resource Center, 615 North Wolfe Street, Room 6001, Baltimore, MD 21205. Contact: Morton Corn (410) 955-3602.

Electronic Resources

The following is a list of web sites along with their Internet address that contain ergonomics-related information and material:

The Human Factors and Ergonomics Society Website	http://hfes.org
The ERGOWEB Homepage	http://www.ergoweb.com
The CTD NEWS Newsletter	http://www.ctdnews.com
Ergonomic Newsgroup	http://www.deja.com/group/comp.human-factors
The OSHA Website	http://www.osha.gov
The Usernomics Home Page	http://www.usernomics.com/news.html
The NIOSH Homepage	http://www.cdc.gov/niosh/homepage.html
Liberty Mutual Website	http://www.libertymutual.com/research/programs/index.html
University of Virginia VDT Ergonomics	http://keats.admin.virginia.edu/ergo/vdt.html
University of Nebraska, RSI Website	http://www.engr.unl.edu/ee/eeshop/rsi.html
Auburn University, OSE Program	http://www.eng.auburn.edu/ie/OSE

FURTHER READING

Sanders, M.S., and E. J. McCormick, *Human Factors in Engineering and Design,* 7th ed., McGraw-Hill, New York, 1993, pp. 23–46.

BIOGRAPHIES

Brian Carnahan received his doctorate in industrial engineering at the University of Pittsburgh. This degree is added to his B.S. in science from the Pennsylvania State University and master's in industrial engineering and operations research from the University of Massachusetts. He has worked extensively as an industrial engineer and ergonomist for the U.S. Department of Labor's Occupational Safety and Health Administration (OSHA) in Washington, DC. In addition, he has held a position as a human factors specialist for the Carnegie Mellon Research Group in Pittsburgh and CMU's Driver Training and Safety Institute. He has also acted as an instructor in industrial ergonomics for Pitt's Department of Industrial Engineering and in applied mathematics for the university's Manufacturing Assistance Center. Currently, Carnahan is an assistant professor in the Industrial and Systems Engineering Department at Auburn University. His research interests have focused primarily upon developing artificial intelligence applications to help solve challenging problems in ergonomics, safety, and health. These applications have focused on the automated design of safe lifting tasks, industrial job rotation scheduling, assembly line balancing, low back injury risk modeling, and skill and accident analyses of long haulage truck drivers. Carnahan is a member of the Human Factors and Ergonomics Society, The Industrial Ergonomics Technical Group, The Institute of Industrial Engineers, The American Society for Safety Engineers, and the Alpha Pi Mu Society.

Mark S. Redfern is an associate professor in the Departments of Otolaryngology, School of Medicine, and Industrial Engineering at the University of Pittsburgh. He has a B.S.E., an M.S.E., and a Ph.D. (bioengineering) from the University of Michigan at Ann Arbor. His research interests are focused on human postural control, ergonomics, and workplace design. He is director of the Human Movement and Balance Laboratories at the University of Pittsburgh. His articles have appeared in *IIE Transactions, Ergonomics, Journal of Safety Research,* and *Human Factors.* He is a member of the American Society of Biomechanics, Human Factors and Ergonomics Society, and IEEE.

Source: MAYNARD'S INDUSTRIAL ENGINEERING HANDBOOK

CHAPTER 6.2

DESIGNING, IMPLEMENTING, AND JUSTIFYING AN ERGONOMICS PROGRAM

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Welcome to the world of applied ergonomics. One of the first things an industrial engineer will realize is that the science of ergonomics is an applied tool for productivity and quality enhancements in any work environment. The science provides an industrial engineer with the knowledge of

- Human capabilities and limitations
- Risk factors associated with the manufacturing tasks
- Basic principles of ergonomics and biomechanics

In this chapter, we will be answering the question, Why Ergonomics? as well as discussing updated industrial trends for engineering, designing an ergonomics program, implementing an ergonomics program, and justifying the need for ergonomics. These four areas will explain why, to whom, and how to sell the ergonomics program through engineering. It is imperative for engineers to become familiar with the science of ergonomics for the improvement of productivity, quality enhancements, and cost controls.

ERGONOMICS BACKGROUND

Definition

> *ergonomics:* n sing or pl: an applied science concerned with the characteristics of people that need to be considered in designing and arranging things that they use in order that those things may be used most easily, effectively, and safely—called also *human engineering, human factors engineering* [1]. A combination of two Greek words *ergo* means work, *nomos* means law; the study of the human response to exposure in the work environment; the interaction between humans and the tools, equipment and work methods needed to complete a task; fitting the task to the employee.

The Science of Ergonomics

Ergonomics is a multidisciplinary science comprised of engineering, mathematics, anatomy, physiology, anthropometry,* psychology, and biomechanics† as illustrated in Table 6.2.1. Ergonomics allows an engineer to understand the human element when considering the design of a job, tool, or equipment. Without the understanding of the employee characteristics, the engineer is unable to meet the physical requirements (e.g., reaches, clearances, cycle times) that would be appropriate for productivity while maintaining the health and safety of the working population. When the employee population is not considered in the job design, issues such as equipment selection and design, work flow, and material flow may impact the bottom line of any company.

Musculoskeletal Stress and Injury

Lack of attention to ergonomics may lead to injury and illness of the worker. There are stressors or risk factors associated with most jobs. The risk factors can produce workplace musculoskeletal disorders (WMSDs),‡ which are subtle and costly injuries and illnesses that can occur in any body part and happen over time. They could include

- Tendonitis—inflammation of a tendon.
- Tenosynovitis—inflammation of the tendon sheath.
- Back injuries—from the neck to the base of the spine.
- Ganglionic cysts—small cystic tumors containing fluid and connected with a joint membrane or tendon sheath.
- Carpal tunnel syndrome—located in a passage between the wrist and hand, it is a condition caused by compression of the median nerve in the carpal tunnel and characterized by weakness, pain, and loss of sensation in the hand.

TABLE 6.2.1 Ergonomic Disciplines

Discipline	Comprised of	Includes
Biomechanics	Engineering sciences Physical sciences	Mechanics Statics Dynamics Physics Physical energy stresses
Work physiology	Physical sciences Biological sciences	Chemistry Biochemistry Anatomy Physiology Physiological stresses
Engineering psychology	Social sciences Behavioral sciences	Anthropology Anthropometry Psychology Sociology Group dynamics

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* The science of measurement and the art of application that establishes the physical geometry, mass properties, and strength capabilities of the human body.

† The mechanical bases of biological especially muscular activity; mechanical engineering of the human body [1].

‡ Same as MSDs, overuse syndrome, repetitive strain injuries, repetitive motion injuries.

- Vibration—hand/arm and whole body.
- Contact or mechanical stress—kneeling or leaning against hard or sharp objects, improperly fitting tools.

Actions contributing to the most common musculoskeletal disorders are described in Table 6.2.2. WMSDs differ from an acute trauma. An acute trauma is one that happens as a result of a single and very defined incident. These may be

- Slips and falls
- Burns
- Lacerations
- Particles in eye

WHY ERGONOMICS? UPDATED INDUSTRIAL TRENDS

To establish an ergonomics program in any company, one must first establish the need. There are several factors to be considered. One is the relationship to current industrial trends and how ergonomics impacts those trends.

TABLE 6.2.2 Actions Contributing to the Development of Cumulative Trauma

Disorder name	Actions contributing to disorder
Bursitis	Arm elevation, adduction, rotation
Cubital tunnel syndrome	Resting forearm near elbow on hard surface or sharp edge, reaching over obstruction
Carpal tunnel syndrome	Rapid, often-repeated finger movements, wrist deviations, pinch grip, vibrations of 10 to 60 Hz
Degenerative joint disease	Trauma, faulty posture of the back, emotional stress
De Quervain's disease	Combined forceful gripping, hand twisting
Elbow tendinitis	Repetitive forceful exertions of forearm, rotations around elbow joint
Epicondylitis	Dorsiflexion, pronation
Facet slipping	Going beyond the limit of sudden movements in back flexion and extension
Frozen shoulder syndrome	Repeated overhead motions
Ganglionic cyst	Force exertion
Guyon tunnel syndrome (ulnar nerve entrapment)	Wrist flexion and extension, pressure on the hyopthenar eminence
Lumbosacral strain	Faulty alignment, standing for long periods unguarded, forward bending
Pronator teres syndrome	Forearm pronation, strong elbow and wrist flexion
Rheumatoid athritis	Overuse or repetitive trauma to the joints
Rotator cuff tendinitis	Arm elevation, arm adduction, elbow elevation
Sacroiliac strain	When back or hamstring muscles are restricted, forward bending movements may affect the sacroiliac joints
Sciatica	May be due to some mechanical factor of compression or tension
Stenosing Tenosynovitis Crepitans (Trigger Finger)	Digit flexion, flexion of distal phalanx alone
Tension Neck Syndrome	Lateral, static movement of the head and neck, flexion/extension of the neck
Thoracic Outlet Syndrome Tight Tensor Fasciae Latae and Illiobial Band	Arm elevations, carrying, shoulder flexion, arm hyperextension, faulty posture of the cervical spine, forward head position
Ulnar Artery Aneurysm	Pounding and pushing with heel of hand
Vibration syndrome	Vibrations between 40 and 125 Hz, tight grip, cold temperatures
Wrist tendinitis	Forceful ulnar deviation and thumb pressure, repetitive wrist motion, forceful wrist extension and pronation

The Bureau of Labor Statistics (BLS), a division of the Department of Labor, keeps track of workplace illnesses and injuries on an annual basis. The BLS relies on workplace injury and illness reporting (OSHA 200 logs) by private industry and is required by the Occupational Safety and Health Administration (OSHA). In 1996, there were 281,100 cases of repeated trauma recorded accounting for 4.5 percent of all 6.2 million injuries and illnesses logged and 64 percent of the 439,000 illnesses recorded. Table 6.2.3 describes the requirements for injury and illness recordkeeping in the United States. Table 6.2.4 shows how different types of injuries related to days away from work.

There are several trends in today's engineering environment that may contribute to ergonomics workplace injury and illness:

- Aging of the U.S. working population
- Increase in women in the U.S. workforce
- An increase of employees from developing countries in the United States
- Reduced physical conditioning of the U.S. employee base
- Downsizing of the employee population
- Global demand for mass-market products
- Global competition for quality and pricing

Aging of the U.S. Working Population

The U.S. labor force is projected to increase by 15 million between 1996 and 2006, from 134 million to 149 million. This represents an increase of 11 percent. The projections indicate that the demographic composition of the labor force is expected to change because the population and workforce participation will change.*

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* BLS 1996–2006 employment projections.

TABLE 6.2.3 Injury/Illness Recordkeeping Requirements

- Under the OSH act, all **work-related illnesses** must be recorded on the OSHA 200 form, even if the condition is in an early stage of development. If the condition is "diagnosed or recognized" as work-related, the case must be entered on the OSHA 200 form within 6 workdays after detection.
- In order to be recordable, the following criteria must be met:
    1) The illness must be work-related. This means that exposure at work either caused or contributed to the onset of symptoms or aggravated existing symptoms to the point that they meet OSHA recordability criteria. Simply stated, unless the illness was caused solely by a non-work-related event or exposure off premises, the case is presumed to be work-related.
    2) A WMSD must exist as evidenced by either physical findings **OR** subjective symptoms and resulting action. Namely, there must be either:
        - at least one physical finding (e.g., positive Tinel's, Phalen's, or Finkelstein's test; or swelling, redness, or deformity; or loss of motion) **OR**
        - at least one subjective symptom (e.g., pain, numbness, tingling, aching, stiffness, burning) and at least one of the following:
            i. medical treatment (including self-administered treatment when made available to employees by their employer)
            ii. lost workdays (includes restricted work activity)
            iii. transfer or rotation to another job
- All **work-related injuries** (including back cases) are recordable if medical treatment, loss of consciousness, restriction of work or motion, or transfer to another job occur.

Sources: Occupational Safety and Health Act and Recordkeeping Regulations—Title 29, Code of Federal Regulations (CFR) 1904 U.S. Department of Labor, BLS, Recordkeeping Guidelines for Occupational Injuries and Illnesses, September 1986 (or later).

TABLE 6.2.4 Percent Distribution of Nonfatal Occupational Injuries and Illnesses Involving Days Away from Work by Selected Injury or Illness Characteristic and Number of Days Away from Work, 1994.

Characteristic	Total cases	1 day	2 days	3–5 days	6–10 days	11–20 days	21–30 days	31 days	Median days
Total	100	16.3	12.9	21.0	13.3	11.2	6.4	18.9	5
Sprains, strains	**100**	**12.9**	**12.8**	**23.2**	**14.9**	**12.1**	**6.1**	**18.2**	**6**
Bruises, contusions	100	23.5	17.6	23.6	12.4	8.1	4.0	10.6	3
Cuts, lacerations	100	26.8	16.0	21.6	13.7	9.2	4.5	8.3	3
Fractures	100	7.7	6.9	12.3	10.8	12.9	11.3	38.0	20
Carpal tunnel syndrome	**100**	**3.4**	**3.6**	**7.5**	**10.3**	**14.6**	**12.0**	**48.7**	**30**
Heat burns	100	19.1	14.9	25.1	15.3	11.6	5.7	8.2	4
Tendinitis	**100**	**11.5**	**8.4**	**18.2**	**14.8**	**14.3**	**8.6**	**24.1**	**10**
Chemical burns	100	32.6	20.4	22.7	10.5	5.9	3.0	4.8	2
Amputations	100	5.3	4.0	9.9	11.2	15.4	14.0	40.2	24

Source: Characteristics of Injuries and Illnesses Resulting in Absences from Work, 1994, USDL-96-163, Released May 8, 1996.

The labor force between the ages of 45 and 64 will grow faster than the labor force of any other age group as the baby-boom generation (born 1946 to 1964) continues to age. The labor force from 25 to 34 years of age is projected to decline by almost 3 million, reflecting the decrease in births in the late 1960s and early 1970s.* As the working population ages, they become more susceptible to workplace injuries/illnesses, production problems, and quality issues. When configuring a pricing strategy for a product or process, it is understood that all costs associated with the production are expensed into the product pricing. Since workers' compensation costs, lost work time, redo work, and quality and productivity problems are factored into the pricing structure, it is important to manage the costs of production to remain globally competitive in today's industrial environment. To do so, the engineer must understand not only the population of end users, but also the population of the employees hired to manufacture and assemble any product. Figure 6.2.1 illustrates changes in the age composition of the labor force for the automotive industry.

Increase in Women in the U.S. Workforce

The labor force participation rates of women in nearly all age groups are projected to increase. The women's labor force will grow more rapidly than the men's. By the year 2008, 48 percent of

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* BLS 1996–2006 employment projections.

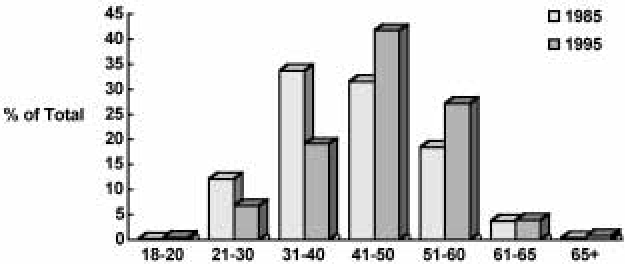

FIGURE 6.2.1 Age breakdown of hourly workers in the Big Three auto companies.

the U.S. workforce will be female.[*] Figure 6.2.2 illustrates the historical and projected figures for the gender composition of the civilian labor force in the United States.

According to Chaffin and Andersson (1991), "on average, women have about two thirds of the strength of men." The largest difference in muscle strength, which is the basic unit for movement during work, is determined by gender. With women possessing about 70 percent of the strength of men, they will not have the same endurance or capacity to perform tasks involving lifting, lowering, pushing, and pulling that men possess. As you continue to read this chapter, you will be able to relate the increase in workers' compensation claims to the increase of women and other factors, such as age, cultural difference, and physical conditioning, to the workplace.

Private sector employers spend about $60 billion annually on workers' compensation costs associated with injuries and illnesses experienced by their employees. The Department of Labor's Occupational Safety and Health Administration (OSHA)[†] has estimated that as much as one-third of these costs are due to work-related musculoskeletal disorders (MSDs),[‡] a wide range of illnesses and injuries related to repetitive stress or sustained exertion of the body.[§] These numbers are more than likely to continue to increase with a greater percentage of women in the workplace.

An Increase of Employees from Developing Countries in the United States

At the beginning of the twentieth century, the majority of immigrants coming to America came from Europe. These immigrants assimilated into the fabric of U.S. culture and brought with them the skills and work ethic of their respective countries. In the last 20 years, the immigration wave has included many developing countries. The "Asian-and-other and Hispanic labor force will grow more rapidly than other groups, 41 percent and 36 percent respectively. The Asian-and-other labor force will increase from 4 to 5 percent and Hispanics from 10 to 12 percent."[¶]

These figures bring an increased challenge to the engineering community. The Asian population is smaller in stature and has less strength capability compared with the U.S. popula-

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[*] BLS 1998–2008 employment projections.

[†] OSHA was created to carry out the Occupational Safety and Health Act, which declared a national policy of ensuring safe and healthful working conditions for every working man and woman. OSHA develops and enforces workplace safety and health standards and educates employers and employees about workplace hazards.

[‡] MSDs also known as CTDs include conditions such as tendonitis, carpal tunnel syndrome, and lower back injuries, which occur in a myriad of occupations, such as assembly workers and computer keyboard operators.

[§] United States General Accounting Office, *Worker Protection: Private Sector Ergonomics Programs Yield Positive Results,* August 1997.

[¶] BLS 1996–2006 employment projections.

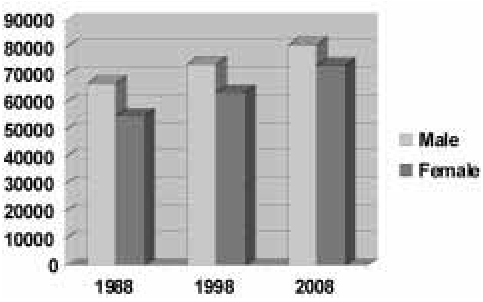

FIGURE 6.2.2 Civilian labor force by gender—1988, 1998, and projections to 2008.

tion. The engineer now has to consider working heights, reaches, manual material handling weights, carry distances, origins of lifts, and destinations of loads for a variety of populations. This has to be considered to prevent injuries and illnesses to smaller employees.

Reduced Physical Conditioning of the U.S. Employee Base

As the wealth of the United States increases, so does the waistline of our employees. The variety and availability of foods have allowed the American population to grow not only taller, but also heavier to the point of being the most obese of any population in the world. The increased weight inhibits employees' movement and endurance and places additional stress on the joints of their body. To reduce the potential for injury from an increasingly unfit workforce, the engineering designs have to consider age, gender, and cultural differences, and the reduced flexibility and endurance of the American employee.

Downsizing of the Employee Population

Today, there is another trend in the industrial environment. Manufacturing's share of total jobs is expected to decline, as a decrease of 350,000 manufacturing jobs is projected. Manufacturing is expected to maintain its share of total output, as productivity in this sector is projected to increase. Accounting for 14 percent of employment in 1996, manufacturing is expected to account for just 12 percent in 2006. This translates to a downsizing of the manufacturing workforce for the purpose of increasing profitability for the major companies in the United States. There will be fewer employees doing more jobs. The jobs must be considered individually as in a rotation schedule or cellular manufacturing environment.

Service-producing industries will account for virtually all of the job growth. Health services, business services, social services, and engineering, management, and related services are expected to account for almost one of every two wage and salary worker jobs added to the economy during the 1996 to 2006 period.* Of the 10 fastest growing industries (see the following list), 9 belong to 1 of these 4 industry groups:

- Computer and data processing services
- Health services
- Management and public relations
- Miscellaneous transportation services
- Residential care
- Personnel supply services
- Water and sanitation
- Individual and miscellaneous social services
- Offices of health practitioners
- Amusement and recreation services

Global Demand for Mass-Market Products

It has been the experience of America's manufacturing companies that some countries have been able to design, manufacture, and assemble products and equipment in a mass-produced environment for a much reduced cost. This makes it difficult to remain globally competitive and American companies have lost market share in electronics, vehicle manufacturing, clothing, and footware, as examples. Among the many costs associated with manufacturing is the cost of labor, which includes workers' compensation, medical claims, lost work time, absenteeism, and training. Most offshore manufacturers do not have the same type of costs, because their labor force is considered expendable. For every one employee injured and unable to return to work, there are many more waiting for the job.

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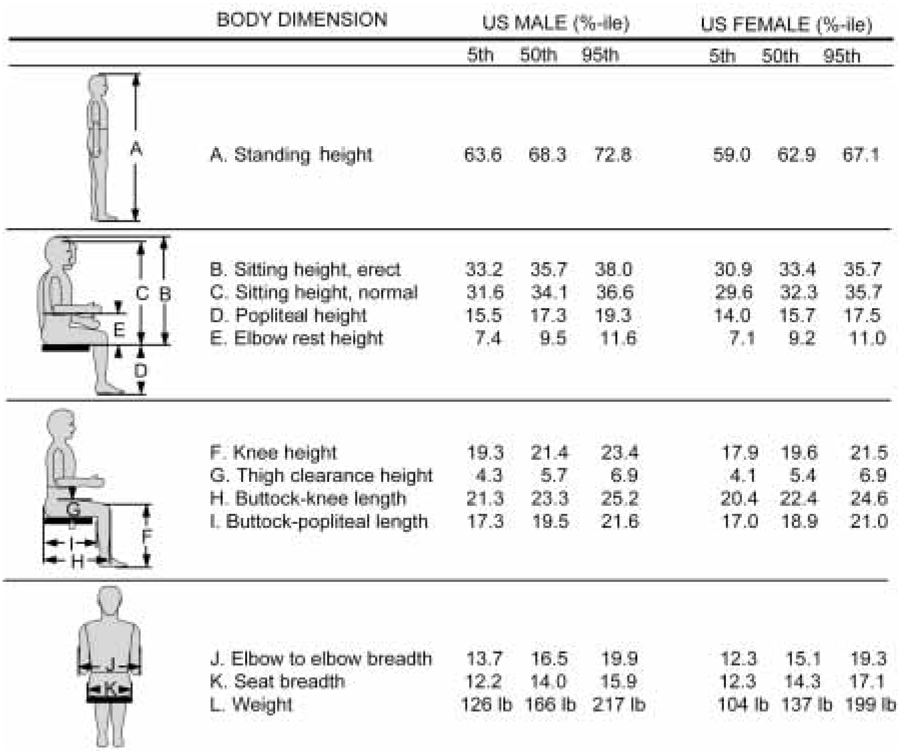
* BLS 1996–2006 employment projections.

These are some of the issues facing engineering in today's manufacturing environments that are related to ergonomics. Engineers can overcome these problems by receiving proper training in ergonomics and biomechanics.

TOOLS FOR ERGONOMIC IMPROVEMENT

There are a variety of tools available to the engineer to assist in the design of work methods, workstations, tools, and equipment that will meet the needs of the changing work environment.

For example, the science of anthropometry allows the engineer to design with specifications that meet the needs of our changing industrial working population. The science is an outgrowth of physical anthropology. It was conceived more than 200 years ago and used in an attempt to distinguish among races and ethnic groups of humans to aid in medical diagnoses. More recently, it has become useful in industrial settings and is identified with the development of engineering design requirements and the evaluation of modern vehicles, work sites, equipment, and clothing [2]. Figure 6.2.3 illustrates some common anthropometric measures that are used in design.


A
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BODY DIMENSION	US MALE (%-ile)			US FEMALE (%-ile)		
	5th	50th	95th	5th	50th	95th
A. Standing height	63.6	68.3	72.8	59.0	62.9	67.1
B. Sitting height, erect	33.2	35.7	38.0	30.9	33.4	35.7
C. Sitting height, normal	31.6	34.1	36.6	29.6	32.3	35.7
D. Popliteal height	15.5	17.3	19.3	14.0	15.7	17.5
E. Elbow rest height	7.4	9.5	11.6	7.1	9.2	11.0
F. Knee height	19.3	21.4	23.4	17.9	19.6	21.5
G. Thigh clearance height	4.3	5.7	6.9	4.1	5.4	6.9
H. Buttock-knee length	21.3	23.3	25.2	20.4	22.4	24.6
I. Buttock-popliteal length	17.3	19.5	21.6	17.0	18.9	21.0
J. Elbow to elbow breadth	13.7	16.5	19.9	12.3	15.1	19.3
K. Seat breadth	12.2	14.0	15.9	12.3	14.3	17.1
L. Weight	126 lb	166 lb	217 lb	104 lb	137 lb	199 lb

FIGURE 6.2.3 Body dimensions of male and female population of the United States.

The engineer assigned to design the tasks to meet the productivity needs must understand which body parts are being stressed during each element of every task. This is the first step from an engineering perspective to reduce the potential for any type of ergonomically related workplace injury or illness.

Table 6.2.5 describes a list of tools an engineer might acquire to keep in an ergonomics toolkit. These tools will provide the ability to identify and measure the stress produced to the body by any portion of the task. With this knowledge, an engineer can design jobs, tools, and equipment that distribute the physical stress on the body rather than having one body part assume the majority of stress.

DESIGNING AN ERGONOMICS PROGRAM

Building Ergonomics into the Corporate Culture

It is very important for the industrial engineer to realize that the earlier an ergonomics program is integrated into the fabric of any corporate culture, the sooner the cost benefits can be realized. To accomplish this, companies must establish an ergonomics program. Ideally, the integration of the ergonomics program is developed when

- A facility is being planned
- The manufacturing requirements are being established
- The tasks are being designed
- A product is in concept phase

Some suggestions for early entry of applied ergonomics into the program are listed in Table 6.2.6. This has become known as the *proactive* approach. It differs from the *reactive* approach based on the assumptions that any potential for ergonomic problems can be identified and abated prior to the creation of symptoms or other warnings such as defects in manufacturing, production errors, quality issues, recalls, workers' compensation claims, OSHA fines/citations, and product liability lawsuits.

Core Elements for Success

Current literature, research, ergonomics experts, and successful organizations agree that to be effective, an ergonomics program should contain a core set of elements. The inclusion of these basic elements is crucial to the success of the program:

TABLE 6.2.5 Ergonomics Toolkit

Tool	To measure
Video camera	Documentation of work motions and tasks
Tape measure	Work surface heights
Biomechanical models (NIOSH, U of MI)	Estimation of joint stresses
Dynamometers	Grip and pinch requirements
Biofeedback devices, electromyography	Muscle activity
Electrogoniometers	Joint postures, angles, and repetitions
Force gauges	Force requirements
Accelerometers, frequency analyzer	Whole body or hand arm vibration
Heart rate monitor	Energy expenditure, used to calculate work: rest ratios
Thermohygrometer	Temperature and humidity
Force-sensing resistors	Contact pressure

TABLE 6.2.6 Applied Ergonomics

• Workplace layout
• Workstation layout
• Equipment selection and configuration
• Tool selection and use
• Work methods
• Rotation schedules or job enlargement
• Return to work programs
• Light duty jobs
• Conservative medical management

- Commitment by management
- Training and involvement of all employees
- Written ergonomics program. Process selection for identification of jobs producing ergonomic risks
- Development and implementation of solutions to abate known risks
- Appropriate medical management

Management Commitment. Management commitment is the first step in the success of any ergonomics program. Management will be approached to allocate personnel and funding to the program. They must participate in the establishment of the program's goals and objectives through the issuance of policy statements and/or written ergonomics programs. Financially approving budget requests in a timely fashion, regarding the ergonomics program's needs for implementation of solutions, will be one way of demonstrating management's commitment to the program. It is crucial for the management team to support the program by demonstrating the employer's belief in the ergonomic efforts, thereby setting the tone for success.

Training and Education

Another component to the implementation of an ergonomics program is training and education. To correctly identify and control WMSDs in any workplace, the engineer is required to have some level of knowledge regarding ergonomics and biomechanics to facilitate the correct redesigns for the workplace, tools, equipment, and processes. The multidisciplined ergonomics team must also be trained in the recognition and identification of ergonomic risk factors. Part of the role of the ergonomics team should be to recommend the type of training necessary for each group in a facility. It is tempting to call all employees into a room and get the ergonomics training over and done. For example, using generic videotapes is very appealing based on the large number of attendees at one time and the relatively inexpensive cost. This approach may seem easy; however, when a subject is new, it may be difficult to grasp from an impersonal approach. It is unlikely that this mass training will provide the attendees with the knowledge and ammunition they need to successfully incorporate ergonomics into their jobs. They may not understand the application for their particular task requirement. Instead, it is advisable to train employees to meet their particular needs for ergonomics awareness.

General Awareness Training. General awareness training in ergonomics and biomechanics, including the recognition of ergonomic risk factors, is a method of "getting everybody to do it and do it right." Bringing all employees up to date in ergonomics is a significant step toward a corporate culture that embraces continuous improvement in engineering, safety, and health. Before the ergonomics training can begin, it is important to have the ergonomics program and process in place. This includes defining the procedures, which are going to be used for risk identification and abatement, the reporting of ergonomic problems, employee participation, and process management. With this structure, it will be possible for the training to incorporate relevant and accurate information on corporate policies and expectations with regard to each employee group.

Management Awareness Training. Managers must be aware of the reason for the ergonomics program and process if they are expected to support it and not squash it. A concise description of the physiologic basis behind ergonomics will suffice. Emphasis should be placed on the benefits of ergonomics, realistic time frames, expected costs, and the role management is expected to play in the overall process. Upper management sends the messages and sets the tone for the success of any program.

Engineering Training. The support of the engineering personnel is essential to ensure that ergonomics improvements are made properly and successfully. In addition to understanding the physiological basis of ergonomics and biomechanics and the relationship between job requirements and injury development, engineers should be trained to use advanced objective measurement techniques for designing ergonomics into workplaces and work processes. These techniques include using anthropometry, applying ergonomic models, and evaluating the consequences of the current work practices. Engineers should be trained using the procedures they should follow to ensure that ergonomics improvements move from concept to reality and that the resources are available to them during each phase of the process. With an ergonomics program, productivity is expected to increase with less wear and tear on the employee base. Therefore, an understanding of human capabilities and limitations is a necessity. When designing a job, the engineer must consider the risk factor of the environment. Ergonomics training provides engineering with the knowledge of environmental issues such as

- Lighting
- Flooring
- Hot and humid environments
- Cold environments
- Vibration, hand/arm (segmental) and whole body
- Noise

During training, the engineer gains an understanding of the type of elements that need to be designed into the work method or tools and equipment under certain situations to reduce the environmental risks. They learn the conditions affecting dynamic work capacity and how energy requirements change based on the ambient temperature and humidity, how overtime affects the body, how to schedule shift work, and the relationship between work and rest cycles.

The engineers have to be more accessible to the supervisors, medical personnel, and line employees; to accomplish this they must spend time on the manufacturing floor to understand how the employees are performing the jobs. It is also important to be familiar with the maintenance of equipment and tools. With an ergonomics toolkit of measurement technologies, the engineer is "armed" to perform assessments in real time, gather data, and redesign tasks that have potential for injuries.

Once familiar with the ergonomics process, the engineering team can develop specifications for work heights, reaches, clearances, cycle times, tool purchases, and equipment purchases. These should be summarized in a formal report. The specifications can be used internally as well as given to company suppliers and vendors to use as a guideline when designing equipment and tools. Table 6.2.7 gives a sample outline for an implementation report.

Supervisor/Line Management Training. Supervisors and line management awareness can provide a valuable method for spotting ergonomics problems at the source. By understanding the do's and don'ts of ergonomics, supervisors can assist employees in the performance of

TABLE 6.2.7 Sample Implementation Report

- Job name
- Baseline assessment summary
- Date
- Results of employee symptom survey
- Ergonomic risk factors identified
- Injury/illness history
- Conclusions
- Solutions considered
- Descriptions
- Projected cost/benefit
- Solution selected and rationale
- Implementation details
- Implementation process (describe steps)
- Start date/completion date
- Responsible contact
- Vendor information
- Costs (actual)
- Results of initial feedback
- Results of 6- to 12-month follow-up
- Level of success or failure
- Action plan

their jobs. In this manner, the least stressful postures, reduced forces, and repetitions can be noted and solutions recommended when feasible. It is very important for supervisors to have a predetermined process for reporting ergonomic problems and for assisting employees in reporting signs of musculoskeletal stress related to job requirements. They can also be trained to recognize when tools, tooling, workstations, and equipment are creating productivity and quality issues that have a relationship to ergonomics.

Line Employee Training. After management, engineering, and supervisory training has been performed and the ergonomics process is ongoing, the line employees must be considered for training. Once the solutions have been implemented into their area of the facility, the employees must be trained on the specific jobs and given a general awareness of ergonomics. The line or hourly employees have a great deal of control over their safety and health, especially when it pertains to ergonomics. Understanding the consequences of awkward posture, excessive force, excessive repetition, vibration, and their general working environment will give the employees the control they need to identify and reduce their injury potential. Learning the signs and symptoms of ergonomic stressors will enable employees to take the necessary steps to change a situation before serious damage occurs. Again, it is very important for employees to know how to deal with these situations and to be reassured that no negative outcome will result form their proactive approach. They also have to be aware of the reporting structure. The employees can also use this information in their recreation and home time to prevent injuries.

Later in the ergonomics process, these employees may be evaluated at the work site and asked to change their work methods in response to ergonomics solutions that are implemented. This awareness training will make these activities all the more relevant for future cooperation.

Ergonomics training is a great beginning and will ensure that the ergonomics process goes smoothly and has the best chance for success. If all those involved share a common goal and a broad understanding of ergonomics, the chances for cooperation and participation are greatly increased. It is also important to understand that through training all employee levels, people become empowered with knowledge. Table 6.2.8 summarizes the various levels of ergonomics training discussed.

TABLE 6.2.8 Levels of Ergonomics Training

Training type	Audience	Approximate length	Frequency
General training	Employees Supervisory management	1–4 hours	Annual, new hire
	Goal: Understanding of ergonomics and the factors associated with the development of occupational musculoskeletal injuries. Techniques and methods for reducing individual risk and exposure to ergonomic stressors. Understanding of the roles and responsibilities of each group in the overall ergonomic process.		
Job-specific training	Employees	As needed	New hire, transfer, or when work requirements change
	Goal: Understanding (through demonstration and hands-on practice) of proper use and procedures for all tools and equipment. Care, use, and handling techniques for knives, use of special tools and devices associated with individual workstations, use of appropriate guards and safety and protective equipment, use of proper lifting techniques and available assistive devices.		
Technical training	Engineers Safety/health Maintenance personnel Medical	2–5 days	Initial and periodic technology update
	Goal: To be able to apply a systematic ergonomics process for preventing occupational musculoskeletal injuries through job and workstation evaluation and design. Includes a thorough background and understanding of the human, environmental, and work-related factors that contribute to the presence of ergonomics hazards.		

Training and Involvement of Employees. Involving employees from all levels is crucial to the success of the design of the ergonomics program. These employees may include but are not limited to

- Management
- Engineering
- Safety
- Health
- Line employees

Involving employees in efforts to improve workplace conditions provides a number of benefits, including enhancing employee motivation and job satisfaction, improving problem-solving capabilities, increasing the likelihood that employees will accept changes in the job or work methods, and improving labor relations.

Employee involvement may include

- Creating committees or teams to receive data on ergonomic problem jobs
- Training members to identify the risk factors through an approved process
- Training members in ergonomics and biomechanics principles for abatement of identified risk factors and conditions
- Training employees to recognize simple ergonomic problems and make recommendations for corrective actions
- Establishing a process to encourage prompt and accurate reporting of signs and symptoms of WMSDs by employees so that these symptoms can be ergonomically evaluated by the team and the work conditions changed if necessary
- Creating an atmosphere that allows employees to be comfortable reporting potential problems and making suggestions for job improvements or conditions

- Having members administer periodic surveys to determine employee reaction to workplace conditions so employees may suggest changes or additional ergonomic evaluations

Written Ergonomics Program. After the management commitment has been confirmed, it is important to implement a written ergonomics program that is endorsed and advocated by the highest level of management. The written program outlines the employer's goals and plans. This program should be suitable for the size and complexity of the workplace operations, and should permit these guidelines to be applied to the specific situation of each facility.

The written ergonomics program is communicated to all personnel, regardless of the number of personnel or number of working shifts. It should clearly establish the goals and the objectives to meet the goals and ensure that communications are clear and concise. The written program should be part of the new employee packet and explained as part of the hiring process.

Ergonomics Process for Risk Identification. Once the policies of the ergonomics program have been developed, it is time to select an ergonomics process for the identification of jobs that may possess ergonomic risk factors. The ergonomics process is used to assess all the jobs and tasks related to a company. The ergonomics team members should then be trained in the process that has been adopted. The ergonomics process is a necessary component to any ergonomics program because it provides information to determine the scope and characteristics of potential ergonomics risks that might contribute to a WMSD. Research has provided a variety of ways employers can identify problem jobs or job tasks. This should also include which body part may endure physical stress from predetermined risk factors. One approach is to identify levels of physical stress to body parts from predetermined risk factors. This allows the company to appropriately place employees who may have work restrictions on activity levels, employees who might be complaining of pain or discomfort associated with a particular body part, or employees who are out of work and need a return to work program.

There are three pieces of evidence to be considered when attempting to identify ergonomic risk:

- Historical data
- Employee feedback
- Ergonomic risk factor assessment
- Observation of job requirement

A description of each type of data follows, and samples of checklists used to organize and gather the three types of data are illustrated in Figs. 6.2.4 through 6.2.6.

Historical Data. The first step is to provide the information that establishes which jobs are to be assessed. A simple way to determine those jobs producing problems for employees is to gather historical evidence. The historical data may be obtained through analyzing:

- Past OSHA recordables
- Medical claims
- Lost work days
- Absenteeism
- Production problems (e.g., greater amounts of redo work)
- Quality issues (e.g., increase in rejects)

This evidence also provides the employer with a road map of jobs needing interventions, based on priorities and an understanding of the budgetary requirements. To establish the priority basis, a numerical value is given to the jobs that have had the most amount of recordables, complaints, lost work days, and so on assigned to them. This will develop a pri-

DESIGNING, IMPLEMENTING, AND JUSTIFYING AN ERGONOMICS PROGRAM

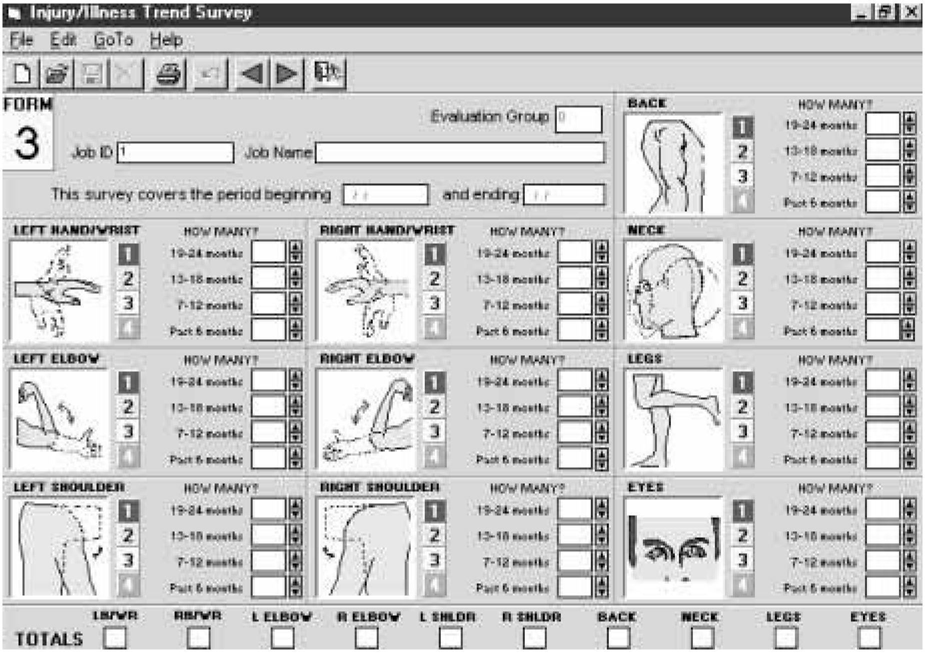
Injury/Illness Trend Survey
File Edit GoTo Help
FORM 3
Evaluation Group
Job ID
Job Name
This survey covers the period beginning
and ending
BACK
NECK
LEGS
EYES
LEFT HAND/WRIST
RIGHT HAND/WRIST
LEFT ELBOW
RIGHT ELBOW
LEFT SHOULDER
RIGHT SHOULDER
HOW MANY?
19-24 months
13-18 months
7-12 months
Past 6 months
1
2
3
4
TOTALS
LH/WR
RH/WR
L ELBOW
R ELBOW
L SHLDR
R SHLDR
BACK
NECK
LEGS
EYES

FIGURE 6.2.4 Ergonomics historical data checklist.

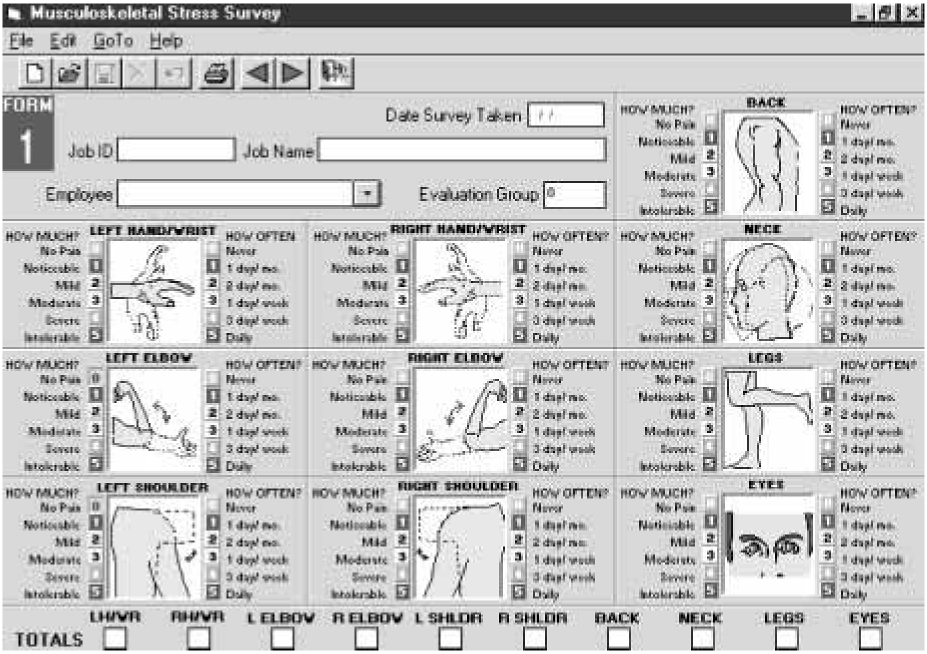
Musculoskeletal Stress Survey
File Edit GoTo Help
FORM 1
Date Survey Taken
Job ID
Job Name
Employee
Evaluation Group
BACK
NECK
LEGS
EYES
LEFT HAND/WRIST
RIGHT HAND/WRIST
LEFT ELBOW
RIGHT ELBOW
LEFT SHOULDER
RIGHT SHOULDER
HOW MUCH?
No Pain
Noticeable
Mild
Moderate
Severe
Intolerable
HOW OFTEN?
Never
1 day/ mo.
2 days/ mo.
1 day/ week
3 days/ week
Daily
TOTALS
LH/WR
RH/WR
L ELBOW
R ELBOW
L SHLDR
R SHLDR
BACK
NECK
LEGS
EYES

FIGURE 6.2.5 Ergonomics employee questionnaire.

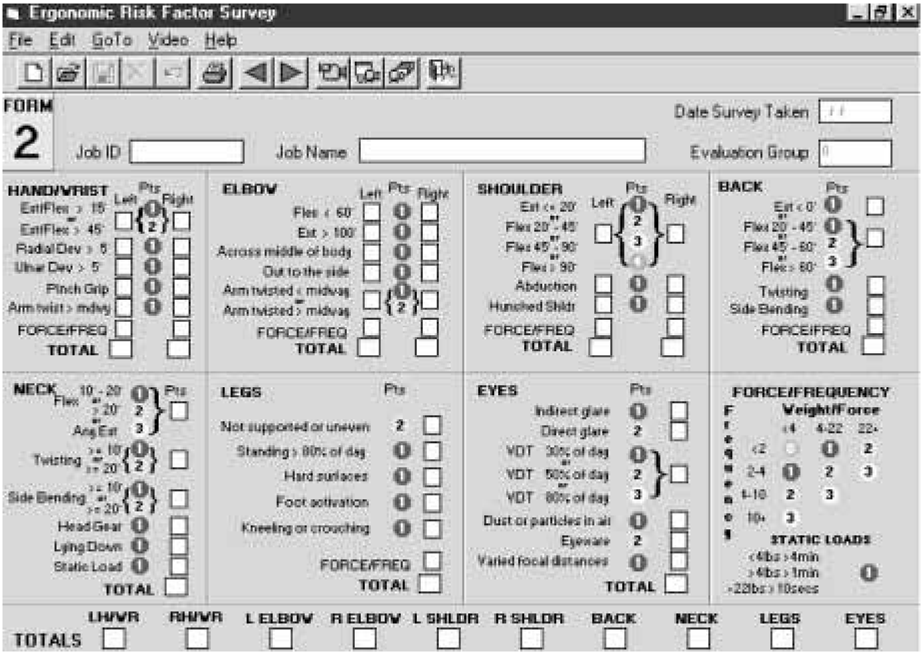
Ergonomic Risk Factor Survey
File Edit GoTo Video Help
FORM
2
Job ID
Job Name
Date Survey Taken
Evaluation Group
HAND/WRIST
Pts
Left
Right
Ext/Flex > 15
or
Ext/Flex > 45
Radial Dev > 5
Ulnar Dev > 5
Pinch Grip
Arm twist > midway
FORCE/FREQ
TOTAL
ELBOW
Flex < 60
Ext > 100
Across middle of body
Out to the side
Arm twisted < midway
Arm twisted > midway
FORCE/FREQ
TOTAL
SHOULDER
Ext <= 20
Flex 20 - 45
Flex 45 - 90
Flex > 90
Abduction
Hunched Shldr
FORCE/FREQ
TOTAL
BACK
Ext < 0
Flex 20 - 45
Flex 45 - 60
Flex > 60
Twisting
Side Bending
FORCE/FREQ
TOTAL
NECK
Flex
10 - 20
> 20
Ang Ext
Twisting
>= 10
>= 20
Side Bending
>= 10
>= 20
Head Gear
Lying Down
Static Load
TOTAL
LEGS
Not supported or uneven
Standing > 80% of day
Hard surfaces
Foot activation
Kneeling or crouching
FORCE/FREQ
TOTAL
EYES
Indirect glare
Direct glare
VDT 30% of day
VDT 50% of day
VDT 80% of day
Dust or particles in air
Eyewear
Varied focal distances
TOTAL
FORCE/FREQUENCY
Frequency
Weight/Force
<4
4-22
22+
<2
2-4
4-10
10+
STATIC LOADS
<4lbs >4min
>4lbs >1min
>22lbs >10secs
TOTALS
LH/WR
RH/WR
L ELBOW
R ELBOW
L SHLDR
R SHLDR
BACK
NECK
LEGS
EYES

FIGURE 6.2.6 Ergonomics risk factor checklists.

ority list with the jobs having the highest numerical value in need of data gathering at the top of the list. As part of the historical review, a written progress report and program update should be communicated to the employees. This is determined through the ergonomics team meetings with the members conducting a regular program review to monitor the progress, time lines, and successes. A semiannual ergonomics program evaluation is recommended.

Employee Feedback. The second piece of evidence is employee feedback, which will establish the current status of the work environment. This data can be collected through a series of surveys conducted during interviews with employees performing the tasks. This data should be assigned numerical values as well. Questions should relate to particular body parts such as

- Neck
- Shoulder
- Elbow
- Wrist
- Back
- Knees
- Legs
- Eyes

Included with the body part information, the survey should include the frequency and severity of pain or discomfort associated with each of the body areas. Numerical factors are given based on frequency and severity with greater weight given to the severest and most recent pain or discomfort.

Ergonomic Risk Factor Assessment. This third piece of evidence is the ergonomic risk factor assessment. This is a more complex approach to identifying the actual risk factors the jobs are producing. Some of the ergonomic risk factors to be identified should include

- Posture
- Force
- Repetition
- Vibration
- Contact/mechanical stress
- Environmental issues

The ergonomic risk factors identification process should be a systematic methodology, which can be checklists or other tools. This approach should provide engineers with the ability to identify workplace hazards and prioritize jobs based on a numerical value. The ergonomic risk factor assessments will include risk factor identification within each job element. This is useful when attempting to create controls for risk abatement without having to reengineer the entire job.

A systematic approach also allows the engineer to go back and reassess the jobs after solutions have been implemented for the purpose of

- Ensuring that the engineering solutions have not created secondary or tertiary risk factors
- Using "before and after" in retraining of employees
- Using "before and after" as a training tool for other engineering personnel
- Applying knowledge gained to any new planned or modified facility, process, materials, and equipment
- Providing cost-benefit/return of investment data
- Providing the results of this assessment to health care providers for use in assigning treatment plans, light duty, and return to work jobs

Observation of Job Requirements. In addition to these three pieces of evidence, employees performing the jobs can be videotaped during the assessment. This provides the engineer with an observation of the job requirements and stressors that can be reviewed as often as necessary to develop engineering or other controls for risk abatement. Still frames can be captured off the video and used in a report to "picture" the moment of risk. If video is not an option, still photos can be used. Other measurements that can be taken to augment the risk factor checklist can be

- Measurement of work surface heights
- Measurement of reach distances
- Biomechanical calculations (i.e., strength capability and joint stress)
- Grip and pinch dynamometers
- EMG (electromyographic studies)
- Goniometry (measurement of joint postures, angles, and repetitions)
- Force sensors

IMPLEMENTING ERGONOMICS CONTROLS

After the jobs are chosen for ergonomics assessments and the systematic worksite processes have been completed, the engineer must design and implement controls to reduce the identified risks. A system for ergonomic risk prevention and control is the next step. Ergonomic risk is prevented primarily by effective designs of the workstation, tools, and work methods. To be successful, the employer's program should use appropriate engineering and work practice methodologies, personal protective equipment, and administrative controls to correct or control ergonomic risk factors. This is accomplished in priority order based on the risk values per job. Those identified with the highest risk values, producing the greatest potential for injury or having the majority of manufacturing concerns, should be reengineered first.

Engineering Controls

Engineering techniques, where feasible, are the preferred method of control because they eliminate or reduce the employees' exposure to the risk factors. These may include redesigning or changing the workstation layout, tools, equipment, material flow, parts, and product transportation. These redesigns will reduce or eliminate exposures such as awkward postures, excessive forces, repetitive motions, vibration, and contact stress. One of the main focuses of an ergonomics program is to make the job fit the person. There are several ways this can be achieved.

Workstation Design. Workstation designs incorporate the accommodation of employees who actually perform the job requirements. Because there is no average person, which is one who would fall into the 50th percentile for height, weight, reach, head circumference, limb lengths, waist circumference, shoulder width, hand breadth, to name some areas of human measurement, the engineer needs to consider other factors. The workspace should be large enough to allow for the full range of required movements, especially where tools are necessary. Some questions to ask are

1. Can the workstation be adjusted to accommodate various heights and reaches of the range of employees?
2. Is the workstation designed to meet the clearance requirements of the 95th percentile U.S. male (large) as well as the reach requirements for the 5th percentile Asian female (small)?
3. Can employees visualize, without any obstructions, all requirements for the job?
4. Are tools accessible to employees of any size?

Work Method Design. The next consideration would be the design of the work methods. Work methods should be designed to reduce

- Static, awkward, and extreme postures
- Repetitive motion
- Excessive force
- Contact/mechanical stress

To be considered with the work methods, is the analysis of the production system to design or modify tasks to eliminate physical stressors.

Tool Selection and Design. Another factor in engineering controls is the tool selection and design appropriate for the end-user population. For any tool, a variety of sizes should be made available to achieve a proper fit and reduce the ergonomic risk associated with tool usage. The appropriate tool should be used to do a specific job based on the anthropometry of the employee base. Tools should be selected based on additional criteria. Here is a partial list of some of the criteria:

- Weight
- Balance
- Grip size
- Handle geometry
- Trigger force
- Temperature
- Vibration levels
- Hose placement
- Handle temperature

Safe and Proper Working Conditions. An effective program for risk control includes procedures for safe and proper working conditions that are communicated and followed by management, supervisors, and workers. These are considered work practices, and one of the key elements to the work practice program is ergonomics. Training is one method used to communicate the work practices program for ergonomics. The training reinforces the proper working postures, biomechanics, and techniques, the need for good physical conditioning, responsibility to maintain safety procedures, and proper care and maintenance of tools and equipment. Through the work practice program, training is done in correct workstation adjustments—retraining employees whose jobs have been reengineered. This is also the program that assists the engineer in developing decision models for modifications to any work practice controls when the dynamics of the workplace have changed. Such adjustments include changes in the following:

- Line speeds
- Staffing requirements
- Type, size, weight, or temperature of the product handled
- Personal protective equipment

Administrative Controls

Some of the considerations for the reduction of ergonomic risk factors offered to engineers are administrative controls. Some examples of the administrative controls are

- Reducing the total number of repetitions per employee by decreasing production rates and limiting overtime work
- Providing rest periods within the job design to allow body parts to rest and recover
- Increasing the number of employees assigned to a job especially during heavy lifting or carrying, or in extremes of ambient temperatures
- Providing job enlargements that provide a greater amount of jobs using a variety of muscle-tendon groups for the employees
- Increasing the number of employees assigned to a task to alleviate risk factors
- Establishing criteria for the maintenance of facilities, tools, and equipment
- Effective housekeeping to reduce slippery work surfaces and related risks such as slips and falls

Medical Management. An employer's medical management program is a very key element in the reduction of ergonomic risk factors. The medical management program emphasizes the prevention of impairment and disability through early detection of injuries, prompt and effective treatment plans, and timely recovery for the employee. Over the years, there has been a lot of research performed regarding the ergonomic risk factors and the need for a medical management program to accompany the other surveillance methods. Recommendations for the medical management of WMSDs are constantly evolving as researchers publish additional literature. It is imperative that the health care providers monitor the developments of these findings and pass the information along to the company.

There are several ways a company can implement a successful and conservative approach to ergonomic injury reduction. One of the best ways to develop a medical management program is to develop guidelines within the ergonomics program that address the following factors:

- Encourage health care providers to become members of the ergonomics team.
- Train the employees in the recognition of ergonomic risk factors.
- Encourage early symptom reporting of WMSDs and ensure that employees will not be discriminated against based on such reporting.
- Ensure that prompt ergonomics assessments are performed on jobs with identified risk factors.
- Train all health care providers in the recognition of ergonomic risk factors and the symptoms they present.
- Encourage health care providers to spend time in the manufacturing facilities to familiarize themselves with elements of the jobs.
- Provide alternative jobs for employees who have reported symptoms that do not affect the same body part (light duty).
- Make sure each work shift has access to a health care person trained to recognize symptoms of WMSDs.
- Maintain stringent surveillance activities for the reporting/recording of information (OSHA 200 logs and medical claim information).

The medical management program should also address [3]

- Injury and illness recordkeeping
- Early recognition and reporting
- Systematic evaluation and referral
- Conservative treatment
- Conservative return to work policies
- Systematic monitoring
- Adequate staffing and facilities

JUSTIFYING AN ERGONOMICS PROGRAM

For years, the science of ergonomics was riddled with problems of acceptance based on the unknown. The unknown factor was cost. Personnel with fiduciary responsibilities considered costs that might be associated with ergonomics built in, and thought that they were part of the cost of doing business.

Cost justifications are typically required for ergonomic controls, as they are for all capital investments. To justify the purchase of the control, the ergonomist typically cites the costs of injuries or the potential costs of injuries if the control is not implemented (GAO 1997).

Ergonomic Opportunity Areas

There are several types of cost the engineer can calculate to create the ergonomic cost justifications. These become the *ergonomic opportunity areas.*

- *Historical costs:* Those associated costs that have been incurred by your company due to unattended ergonomics problems. Knowing the historical costs is important as it establishes a baseline for understanding the success of your ergonomics efforts. It also provides the engineer with a case to present to management to gain ergonomics program support.
- *Projected savings:* Potential savings can be estimated based on the historical costs and a set of defined assumptions. Projecting potential savings is often used during the decision-making process in conjunction with traditional financial analysis techniques. It is common to also estimate the time frame during which savings can be expected to accrue.
- *Actual cost savings:* Actual cost savings are based on the historical costs compared with the reduced costs following intervention with consideration for the costs associated with implementation. The most important thing the industrial engineer has to do is to calculate *actual* financial savings due to ergonomic interventions. By doing this, the engineer can accomplish several things. First, you have the opportunity to validate and/or refine the assumptions used in the projections. This improves your ability to make even more accurate projections for the future. Second, the engineer can contribute to the body of knowledge regarding the benefit of ergonomics interventions. Third, the engineer can produce tangible results that can be presented to management to illustrate the potential for ergonomics throughout the organization.

Specific Costs of Ergonomic Problems

Without ergonomics programs in place, U.S. companies began to experience increases in the negatives associated with doing business. They were

- Increased workers' compensation claims
- More lost work time
- Higher medical claims costs
- Increased material costs
- Higher turnover of labor
- Less production output
- Increased errors
- More negative quality issues
- Increased product liability issues
- Product recalls
- Negative labor relations

Examples from Industry

"The big three automakers have revealed that $900 of every car they manufacture is spent to care for an occupational injury or illness" [4]. The cost to do business in the United States was skyrocketing and there was little consideration given to managing these costs. Consequently, a lot of manufacturing jobs went offshore. Industrial engineers are responsible for the productivity elements within a company. Productivity is tied to profitability and that generally means employees are going to be working faster.

"A recent study by the Rand Corporation estimates that the direct costs of work accidents were $83 billion for 1989 and that workers' compensation premiums cost American industry more than $60 billion annually. Counting other costs, such as production delays, damage to equipment, and recruitment and training of replacement workers, the total cost for one year is approximately $350 billion [5]. Ergonomic-related injuries and illnesses make up a sizable portion of these losses" [3].

Legal Issues and Costs

Aside from the obvious workers' compensation claims, companies have additional legal costs. These costs might arise from a lawsuit brought by an employee. According to the California Workers' Compensation Institute (CWCI), litigation was nearly universal among cumulative injury claims. It was reported by the CWCI that 94 percent of the WMSD-related claims were litigated. The nonprofit research institute also reported that employers paid 33¢ in litigation costs for every $1 paid in benefits for cumulative injury cases. This can be compared to less than 15¢ for every $1 of incurred benefits for other types of injury claims. Lawyers are hired to obtain a larger permanent disability settlement.

OSHA violations* with penalties are another legal issue for a company. Citations are currently issued under the general duty clause [(5)(a)(1)] of the Occupational Health and Safety Act. In the August 1998 (vol. 7, no. 8) issue of the *CTDNews* the headline reads, "OSHA targets 1998 for draft, summer 1999 for proposal." This pertains to the draft of a national ergonomics standard. It goes on to say that "about 80 percent of the regulatory text is complete." If the standard for ergonomics is adopted, it will change the way OSHA can cite for ergonomics violations. The fines would depend on the size of the company, the number of cited violations, and an employer's willful disregard of employee safety, or the good faith effort an employer demonstrates in attempting to institute an ergonomics program and abate identified risks.

With many companies experiencing organizational downsizing, just as in the case of a catastrophic injury, those employees remaining must assume greater workloads and responsibilities [6]. With today's manufacturing processes, employees tend to be highly skilled and productivity can suffer greatly if these employees become injured.

U.S. Government Assessment of Costs

In August 1997, the U.S. General Accounting Office (GAO) developed a report on ergonomics at the request of Congress. The report titled "Worker Protection, Private Sector Ergonomics Programs Yield Positive Results" was presented to Edward M. Kennedy, Ranking Minority Member, U.S. Senate Committee on Labor and Human Resources, and to Major Owens, Ranking Minority Member, U.S. House of Representatives Committee on Education and the Workforce. The report identified the core elements of an effective ergonomics program, conducted a complete literature review, and interviewed experts in business, labor, and academia. All of the experts had experience in the implementation of programs or expertise in the field of ergonomics.

There were five companies selected for the case studies:

- American Express Financial Advisors
- AMP Incorporated

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* Since the early 1990s, at least six state-operated programs have legislated requirements for employers to develop and implement comprehensive work-site safety and health programs. Oregon requires committees to review OSHA 200 log data to determine whether WMSDs are a problem, and if so, take corrective actions. North Carolina established a partnership in 1994, between the state Department of Labor and the University of North Carolina. The partnership provides on-site evaluations and other services to reduce OSHA violations.

- Navistar International Transportation Corporation*
- Sisters of Charity Health System
- Texas Instruments

Table 6.2.9 shows the employers and facilities selected, their products or services, and their staffing levels.

The results were dramatic and although the ergonomics programs at all of the case study facilities incorporated the core elements suggested in this text, there were often significant differences in how they were implemented. The differences were based on the vast differences in the facilities' industries and product lines, corporate cultures, and experiences during the programs' evolution. Solutions did not typically require significant investment or resources and did not dramatically change the job or operation.

Management at all facilities agreed that their ergonomics programs yielded benefits, including reductions in workers' compensation costs associated with WMSDs. There was also a reduction in overall injuries and illnesses as well as in the number of days injured employees were away from work. There was an improvement in employee morale, productivity, and product quality.

The five companies involved in the GAO study had all practiced the following elements:

- Management demonstrated commitment by assigning staff to be specifically responsible for the ergonomics program
- Established goals and accountability mechanisms
- Integrated ergonomic principles into equipment design
- Made resources available for the program
- Ensured that middle management support was sustained
- Employee involvement was demonstrated through teams; employees had direct access to ergonomic services
- Established procedures so employees could directly access services
- Administered surveys and conducted campaigns

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* Navistar is the only unionized facility in the GAO review.

TABLE 6.2.9 Employers and Facilities Selected for GAO Study

Employer	Facility and location	Product or service	Staffing level
American Express Financial Advisors, Inc.	Headquarters, Minneapolis; MN	Financial planning and other investment services	5300
AMP Incorporated	Electronic connectors manufacturing facility; Tower City, PA	Electronic connection devices production	300
Navistar International Transportation Corporation	Truck assembly facility; Springfield, OH	Heavy and medium duty truck assembly	4000
Sisters of Charity Health System	St. Mary's Regional Medical Center and St. Marguerite d'Youville Pavilion; Lewiston, ME	Medical and nursing home care	780
Texas Instruments	Defense systems and electronics manufacturing facility; Lewisville, TX	Radar, navigation, and missile guidance system assembly	2800

- A simple, incidence-based process was used to identify problem jobs
- Identified jobs on a proactive basis
- Created a process to analyze problem jobs and develop controls
- Developed controls by brainstorming and using in-house resources
- Focused on low-tech engineering controls
- Targeted training to specific groups of employees
- Linked the ergonomics program to medical management programs

Figures 6.2.7 to 6.2.9 highlight the results achieved by the case study facilities after introducing an ergonomics program.

Figure 6.2.8 shows the reduction in the average cost per WMSD or MSD workers' compensation claim for case study facilities.

Figure 6.2.9 shows the reduction in injury and illness incidence rates at case study facilities.

The conclusions found by the GAO study was that

> currently, billions of dollars are spent by the private sector employers on workers' compensation claims associated with MSDs and hundreds of workers each year suffer from MSDs. Our work has demonstrated that employers can reduce these costs and injuries and thereby improve employee health and morale as well as productivity and product quality. More importantly, we found that these efforts do not necessarily have to involve costly or complicated processes or controls, because employers were able to achieve results through a variety of simple, flexible approaches.

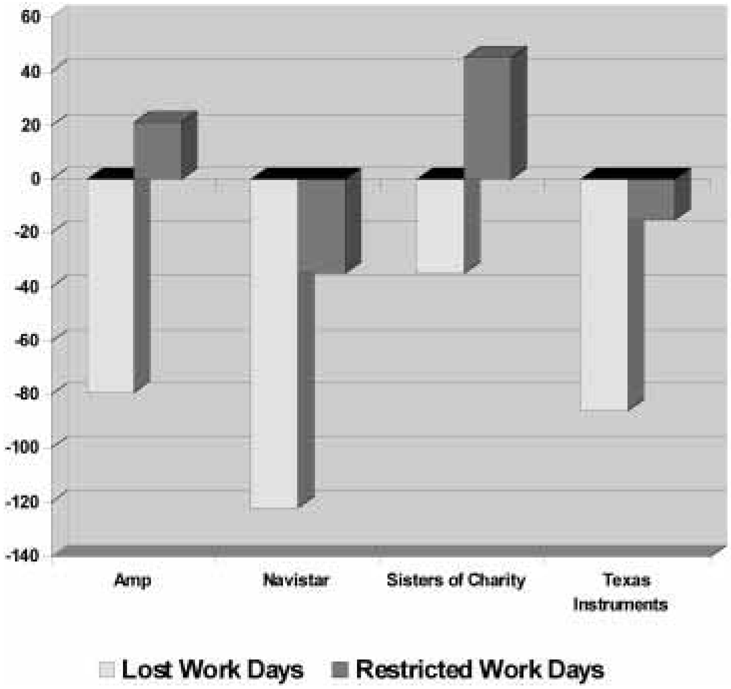

FIGURE 6.2.7 Change in lost and restricted workdays for case study facilities. Source: GAO analysis of case study facilities' workers' compensation databases

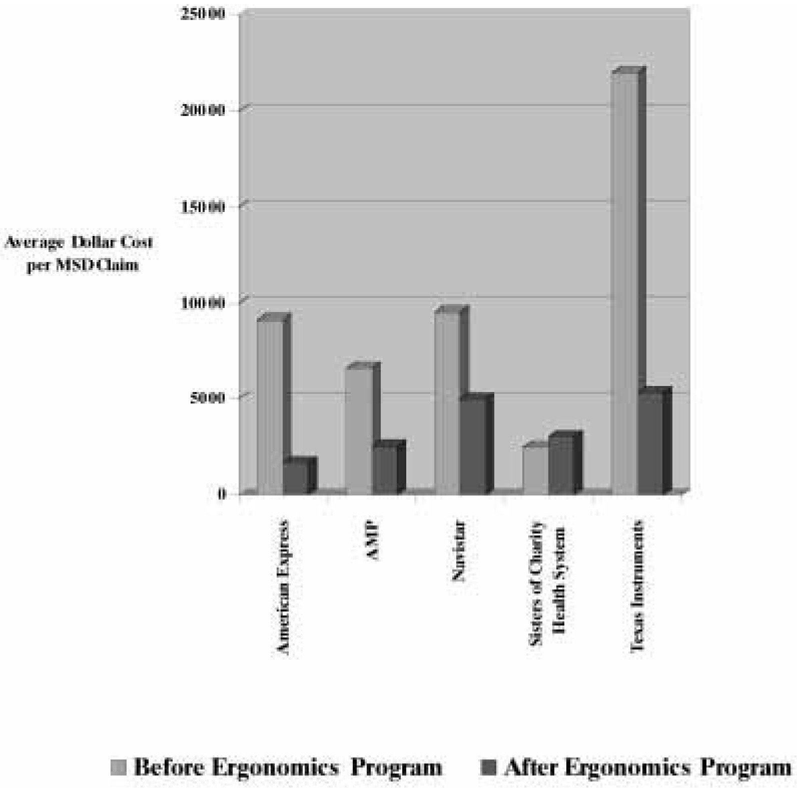

FIGURE 6.2.8 Average cost per MSD workers' compensation claim for case study facilities.

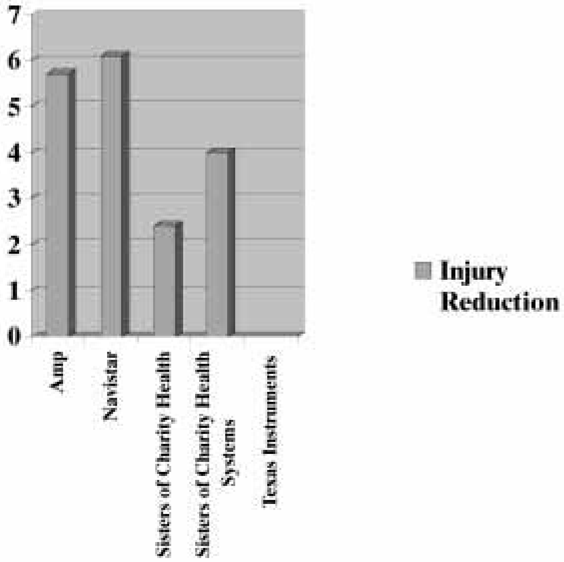

FIGURE 6.2.9 Reduction in injury and illness incidence rates at case study facilities.

In addition to the costs associated with workers' compensation, medical claims, and lost work days due to ergonomically related injuries and illnesses, another major source of costs is the costs associated with legal issues. The OSHA Ergonomics Standard was signed by executive order on November 14, 2000. The federal agency can cite a company for violations based on the OSHA rule or the general duty clause of the Occupational Safety and Health Act. Citations can be quite substantial.

There are several states that have adopted Ergonomics Rules as we go to press. They are:

Washington State
North Carolina
Maine

The engineer must always be aware and ready to act when companies experience poor production or quality issues arise. There are indirect costs associated with time spent investigating incidences, accidents, and injuries; dealing with state and federal officials; and retraining replacement employees. There is also a strain on the medical, safety, and human resources departments.

Ergonomics Program Advantages

Some of the advantages to instituting and maintaining an ergonomics program are

- Decreased errors and product defects
- Justified automation/mechanization
- Improvement in ergonomic risk identification and controls
- Improved quality
- Increased safety and awareness
- Improved productivity
- Better labor relations and employee morale
- Decreased redo work
- Decreased costs for material waste
- Reduced liability of lawsuits
- Reduced risk of citations and fines

Today's business world is global and very competitive. A successful company must implement effective workplace ergonomics standards and provide a safe environment for its workers so that it may enjoy the benefits of improved productivity/quality, improved employee morale, and lower costs associated with workers' compensation.

Measurement Techniques

Cost Avoidance. To reduce companies' manufacturing costs and prove cost reduction, engineers must be able to understand the companies' current actual costs spent for manufacturing. *Cost avoidance* means to prevent potential costs associated with the manufacturing if no interventions are implemented. Often, tomorrow's potentials become today's realities very quickly. As an example, one back injury per employee may cost the company more than $100,000. Cost reductions are typically achieved by increasing productivity (employee output) and reducing labor costs (downsizing). Cost avoidances are primarily achieved by preventing future ergonomic risks factors, which would reduce the potential for injuries, such as those to the lower back. Illustrations of cost reductions are presented in the following sections.

Officials at all of the facilities GAO visited believed that their ergonomics programs yielded a reduction in workers' compensation costs, and other benefits. For example, by identifying a newly automated way of extracting remnant metals when electronic connectors were stamped, the AMP facility not only eliminated awkward positions for employees but also reduced the volume of scrap waste and enhanced the quality of recycled metals made from these scrap metals (GAO 1997).

Other cost justifications include product recalls whereby companies are forced into an ergonomic redesign, poor labor relations where the organized employees force a company into an ergonomic intervention and other factors based on production flexibility, and public image.

> Ergonomics can be implemented using traditional cost benefits, but you have to balance it with the social aspects of health/safety and what's correct to do (CTDNews 1996).
>
> Facility officials also reported improved employee productivity, quality and morale since they had implemented the programs, although evidence of these outcomes was primarily anecdotal. For example, some facility officials said employees are more likely now to exercise control over their jobs and to be more actively involved with line supervisors in how jobs are performed. Officials from Sister of Charity believed that turnover and absenteeism had been reduced and they had been able to hire better employees as a result of their efforts (GAO 1997).

The following examples of cost avoidance clearly demonstrate that American companies are seeing the economic value of ergonomics.

> *General Motors:*
>
> At a General Motors facility responsible for manufacturing and assembling large truck transmissions, management made a decision directly related to ergonomics. Prior to the purchase of $287 million worth of equipment, all vendors and suppliers of the new equipment were given ergonomics specifications regarding workstation designs, work method designs, tools, equipment, heights, reaches, clearances access, forces, maximum weights, carry distances, and so on. This enabled the company to create cost avoidance efficiencies with their suppliers.
>
> *Chrysler Corporation:*
>
> Another example is the Chrysler Corporation, which in July 1998 established a Do's and Don'ts Ergonomic Buyoff form that all vendors and suppliers must adhere to. It is available on the Chrysler intranet and all vendors must have it signed by a Certified Professional Ergonomist (CPE) prior to delivering a design, product, or process to any Chrysler facility. The CPE must evaluate the product or process to determine if there are any ergonomics risk factors present. The company has stated that no purchase orders will be released unless the purchasing agent has a copy of the signed buyoff.

Standard Economic Measures. The most widely used economic measure for cost justification is the net present value of expected cash flows based on the time value of money. Along with net present value as a measure of overall economic worth of a project, the decision maker may use other standard economic measures such as payback period or amortization, which give a measure of how long invested moneys will be used by a certain project and cannot be used for other projects. There are also other valid measures such as rate of return, return on investment, and cost-benefit ratios.

CONCLUSION

The industrial engineer needs to understand the potential engineering results and the necessity to incorporate an ergonomics program in any company. Size does not matter; if a mom and pop operation with 10 employees has 2 employees absent because of an ergonomically related injury or illness, the small company attempts to operate with only ⅘ of the workforce. This can be devastating to any small operation.

Source	Type of information	Contact
Bureau of Labor Statistics (BLS) Contact: Jim Barnhardt	Injury data, costs, and trends Lost work data All OSHA recordables	Tel: 202-606-6179 Fax: 202-606-6196 Web site: www.gov.com (search for *OSHA*)
CTDNews Contact: Mike Gauf	Up-to-date general information on ergonomics, by subscription	Tel: 516-643-5725 Fax: 516-253-4651 Web site: www@http://ctdnews
Ergonomic Technologies Corp. Contact: Cynthia L. Roth	Ergonomics engineering consulting company specializing in workers' compensation reduction, training, product evaluation and design, and software products to manage ergonomics engineering, safety, and health	Tel: 516-922-2828 Fax: 516-922-2876 Web site:www.etcnewyork E-mail: etcnewyork@aol.com
National Institute for Occupational Safety and Health (NIOSH) Contact: Linda Rosenstock, M.D.	Research/development branch of Centers for Disease Control Publications on CTDs	Tel: 800-35-NIOSH Fax: 513-533-8573 Web site: www.cdc.gov/niosh/homepage.html E-mail: pubstat@cdc.gov
North Carolina State University Contact: Dr. Gary Mirka	Education, research, academic studies	Tel: 919-515-6399 Fax: 919-515-5281 E-mail: mirka@eos.ncsu.edu
Ohio State University Contact: Dr. William Marras	Education, research, academic studies	Tel: 614-292-6670 Fax: 614-292-7852
Occupational Safety and Health Administration (OSHA) Contact: Gary Orr, ergonomist	Responsible for all health and safety of the American worker	Tel: 202-219-6478 Fax: 202-219-7068 Web site: www.gov.com (search for *Department of Labor*)
State University of New York-Buffalo Contact: Dr. Colin Drury	Education, research, academic studies	Tel: 716-645-2357 Fax: 716-645-3302 E-mail: INDDRU@UPVMS.CC.BUFFALO..BUFFALO.EDU
Texas Tech University Contact: Dr. M.M. Ayoub	Education, research, academic studies	Tel: 806-742-3543 Fax: 806-742-3411
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DESIGNING, IMPLEMENTING, AND JUSTIFYING AN ERGONOMICS PROGRAM

The type of operation does not matter because ergonomics benefits the service organization as well as the manufacturing environment. Office ergonomics is as important as manufacturing ergonomics. Health care workers in an acute care or chronic care environment must be able to perform their tasks safely and efficiently. Patients depend on their attendance at work. Mail carriers must be able to deliver their products in a timely and safe fashion to keep both consumer and business information flowing.

Industrial engineering has been in the forefront of change in both products and processes since the beginning of the Industrial Revolution. Engineers have had the responsibility to build it faster, cheaper, and better. It is imperative to understand the human response in relationship to the jobs, products, and services that engineers design. The goal is a seamless interface between the human and the task requirement, no matter what type of job the employee is asked to perform. This is the only way we will be able to manage the costs, employee pain and suffering, and global competition that American companies face today and in the future. The science of ergonomics allows engineers to identify, control, and manage the costs of the future of the American manufacturing environments.

ADDITIONAL ERGONOMICS RESOURCES

To assist the industrial engineer here are some additional resources that you might want to investigate to increase your educational and awareness needs in the science of ergonomics.

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BIOGRAPHY

Cynthia L. Roth is the founder and president of Ergonomic Technologies Corporation. She has extensive experience in presenting ergonomics seminars to a large variety of industries and special interest groups and has conducted many training programs at the upper management, medical, supervisory, and line-staff levels. Roth received a degree in nursing from the University of Pittsburgh with a specialty in occupational nursing and biomechanics. She has also completed postgraduate work at Cornell in labor relations/industrial management. She is a member of the National Safety Council, Executive Committees for Aerospace, Metal Tooling, Automotive, and Public Utilities; American Society of Safety Engineers (ASSE); American Industrial Hygiene Association (AIHA); American Foundrymen's Society; and American Health Care Association.

CHAPTER 6.3

ERGONOMIC CONSUMER PRODUCT DESIGN

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Tufts University
Medford, Massachusetts

A brief discussion of an ergonomic design process for consumer products is presented to put one of its methods into perspective. This method, called *morphological ordering,* is particularly useful in ergonomic product design and is presented both as an example of such methods and as a technique for the potential use of the reader. This method can be used when there are different versions of a product for study such as happens in highly competitive product markets. Morphological ordering views the different designs as separate solutions to the design challenge and studies them in a systematic fashion by extracting design-useful measurements and observations from them and then manipulating this extracted data to achieve the design objectives. Several of the uses or objectives of this technique are briefly discussed and an example of how the data could be used to solve a complex design problem is given in some detail. The power of the morphological ordering method is that the different existing designs span the design-variable space to a considerable extent given a sufficient number of them, thus forming a preexisting set of solutions in design space.

INTRODUCTION

Consumer products are one of the most challenging types of products for human use to develop. This is true largely because consumers have choices and, unlike military or industrial users, they need not purchase, use, or repurchase a particular design. Designing consumer products is largely about creating a design that is satisfying in many important respects to the potential user.

When one thinks of consumer product design, it may be in terms of the activities for managing the resources such as time, money, scheduling, and so on, which are typically the responsibilities of a product manager [1]. Management schools teach processes and techniques for the management process but not for creating the product. Others (particularly engineers or design engineers) may think of design as the engineering required to realize a given concept. Still others (particularly industrial designers) may think of design as the intellectual and artistic activity that produces the initial concept for later realizations. This chapter will address the concerns of the latter type of designers. Many of these designers would argue that product design *per se* is essentially a creative activity and as such not subject to rules or to being systematized. Moreover, (creative) design can also be argued to be an irrational process in the sense that it cannot be "rationalized" or captured in logical or algorithmic formats. However, experience has indicated that product design has both analytical elements that are logical and synthetical ones that are closer to the pure creativity aspects, and perhaps cannot be strictly formatted in the algorithmic sense.

A Consumer Product Design Process

The ergonomics of consumer product design have received increasing study and attention over the last several decades both in terms of attending to the ergonomics aspects of products [2] and as a process resulting in a product to uncover and/or impose some order on the process [2–4]. Such attempts generally conceptualize and fractionate the total process into a time line of separate activities or phases taking the form of an outline diagrammed as a sequence of steps. Such a process is shown in Fig. 6.3.1.

This figure sections the product design process into an orderly set of steps (phases) addressing the concerns indicated for each phase. The process shown is normative because it indicates the necessary activities and a general order in which they should be performed to maximize the likelihood of developing a commercially successful product as efficiently as possible. Each phase supplies specifications for the new design as well as generates questions as inputs for the successive phases. Listening to the consumer (Consumer Phase) very early in the process is vital to increasing the chances of producing a successful product (one which returns sufficient money to the producer to cover all of the investment costs incurred by the product and still provides a satisfactory profit). Although each of the phases in Fig. 6.3.1 would require a separate chapter for a full explanation, one method indicated in the Information Phase called morphological ordering will be examined in this paper. The phases in the process depicted in Fig. 6.3.1 point out special activities and are ordered so as to increase the likelihood of developing products that really address the most important concerns or needs of the potential consumers. The first five phases represent analytical work that is completed to develop a set of specifications (or requirements) for the design that effectively "box in" the solution region. This reduces the likelihood of producing solutions that when commercialized are found to be failures because, while perhaps novel and creative, they do not really address those concerns most important to users. Because these specifications are developed from the separate activities, they may contain conflicts. Such conflicts must be resolved in the creative phases that are mounted *after* the problem has been well understood. Creativity must be fully exercised in the creative design session and in the conceptual design phase but within the context of the requirements uncovered in the previous phases. The creative design session and the conceptual design phases differ because the creative design session finds as many different ways to meet each specification as creative thinking can produce. Then, in the conceptual design phase, the best of these are joined to form one or more complete concepts for the product. It is desired that a few, rather than many, different concepts emerge at this point because of the time and expense needed to test each of the concepts.

Other conceptualizations of the design process are similar—but with the important exception that, unlike the presentation in Fig. 6.3.1, they usually emphasize *iteration* as an essential activity throughout the process, which can be depicted by arrows leading from a "downstream" activity back to one or more "upstream" ones. However, because of the pressure to move from a concept to the marketplace as rapidly as possible, iteration, which implies going back and redoing something and retraversing one or more previous steps, is rarely a desirable feature from a management point of view. The process of design can thus be seen as having analytical (logical) sections encompassing the Definition through the Specification phases) and synthetical ones. The major synthetical activities are conducted in the Creative Design Session and Concept Design phases.

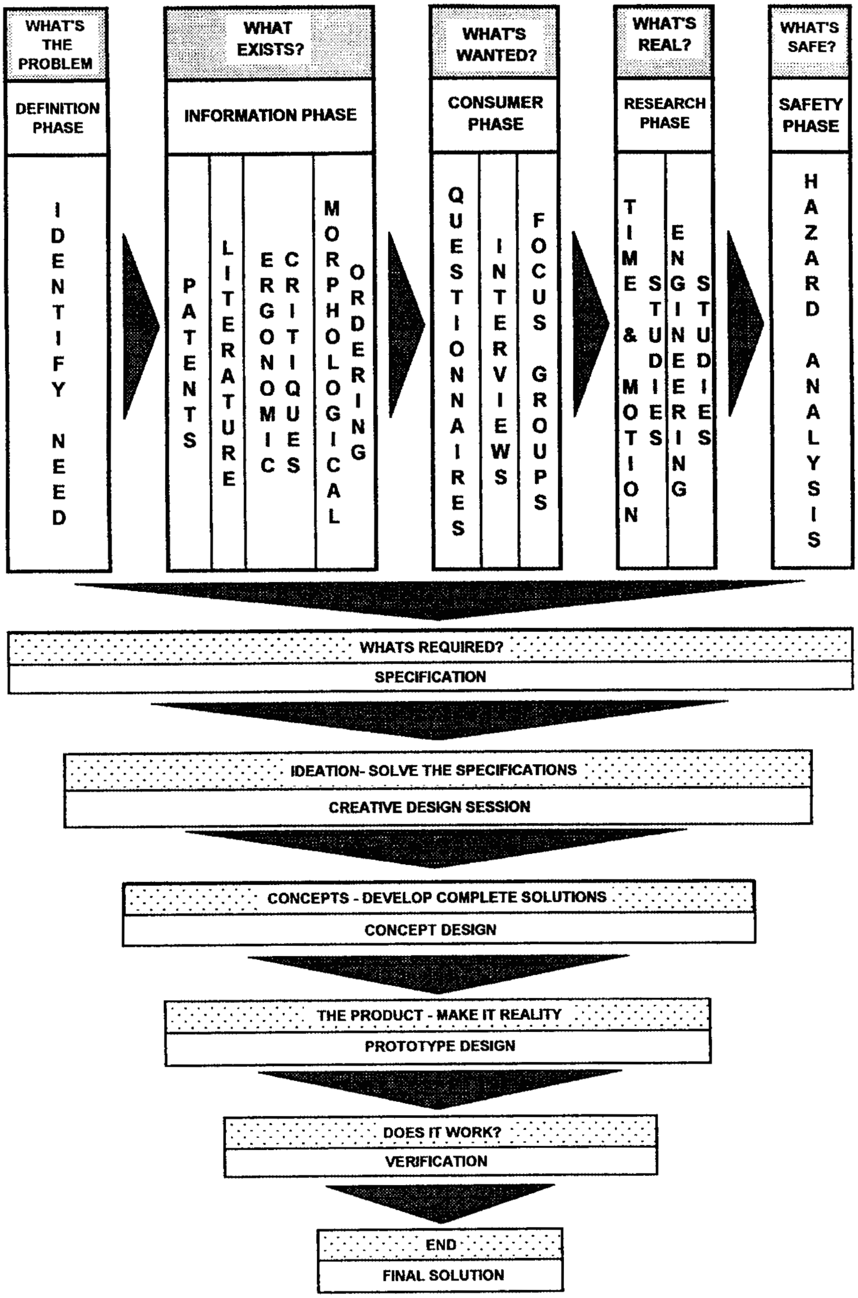

WHAT'S THE PROBLEM
DEFINITION PHASE
IDENTIFY NEED
WHAT EXISTS?
INFORMATION PHASE
PATENTS
LITERATURE
ERGONOMIC
CRITIQUES
MORPHOLOGICAL
ORDERING
WHAT'S WANTED?
CONSUMER PHASE
QUESTIONNAIRES
INTERVIEWS
FOCUS GROUPS
WHAT'S REAL?
RESEARCH PHASE
TIME & MOTION
STUDIES
ENGINEERING
STUDIES
WHAT'S SAFE?
SAFETY PHASE
HAZARD ANALYSIS
WHATS REQUIRED?
SPECIFICATION
IDEATION- SOLVE THE SPECIFICATIONS
CREATIVE DESIGN SESSION
CONCEPTS - DEVELOP COMPLETE SOLUTIONS
CONCEPT DESIGN
THE PRODUCT - MAKE IT REALITY
PROTOTYPE DESIGN
DOES IT WORK?
VERIFICATION
END
FINAL SOLUTION

FIGURE 6.3.1 A consumer product design process.

Different Consumer Product Design Problems

There are several different types of ergonomic design problems that differ in some fundamental ergonomic respects. Figure 6.3.2 contains simple definitions of these different problem types.

The systems are different enough that they represent different conceptual paradigms as will be illustrated for the man-Product system design problem. The man-Product type of problem is one of the most difficult and challenging ergonomic design problems because user preferences, satisfaction, and aesthetics aspects are paramount, in addition to the other more usual ergonomic concerns. The remainder of this chapter will focus on this type of design problem.

User-Product-Task Paradigm

In addition to a process, the consumer product designer also requires a paradigm that encapsulates the design problem in a form suitable for providing a conceptual underpinning for the special nature of many consumer product design problems. A paradigm developed for this particular class of problems is shown in Fig. 6.3.3.

The paradigm calls attention to the two critical design areas: the manipulation interface, which tends to be a primary receiver of ergonomic attention, and the engagement interface to which engineering attention is strongly directed. Such a paradigm, in a fashion similar to the classical feedback control paradigm, helps structure the design problem conceptually. The paradigm emphasizes that there are three legitimate design objects (user, product, task) coupled by the two interfaces (manipulation, engagement), which are acted upon by the four interactions indicated by the feedback and feed-forward arrows. Experience has shown that the requirements of the task are the main determiners of how a product will be manipulated,

ERGONOMIC ISSUES IN DIFFERENT
ERGONOMIC SYSTEMS

SYSTEM	EXAMPLES	ISSUES
MAN - PRODUCT	hair dryers, razors, toothbrushes scalpels, mice, screwdrivers, ...	anthropometry, biomechanics, psychophysics, preferences, aesthetics, satisfaction, sensory psychology, performance, safety, ...
MAN - MACHINE	powered prostheses, industrial machines, sewing machines, power plants, ...	anthropometry, biomechanics, decision making, dynamic behavior, control/display, safety, information handling, ...
MAN - COMPUTER	pc's, laptops, data entry systems, vcr's, calculators, video games, ...	information handling, errors control/display, cognition, ...
MAN - INFORMATION	signing systems, instructions, warnings, manuals, ...	information, organization, perception, vigilance, ...
MAN - WORKPLACE	furniture, seating, lighting, automobile cockpits, ...	safety anthropometry, biomechanics, sensory systems, control/display, productivity, work/rest, ...
MAN - MAN	work cells, operatory teams, projects, ...	queuing, optimization, group dynamics, organization, ...

FIGURE 6.3.2 Different ergonomic consumer product design problems.

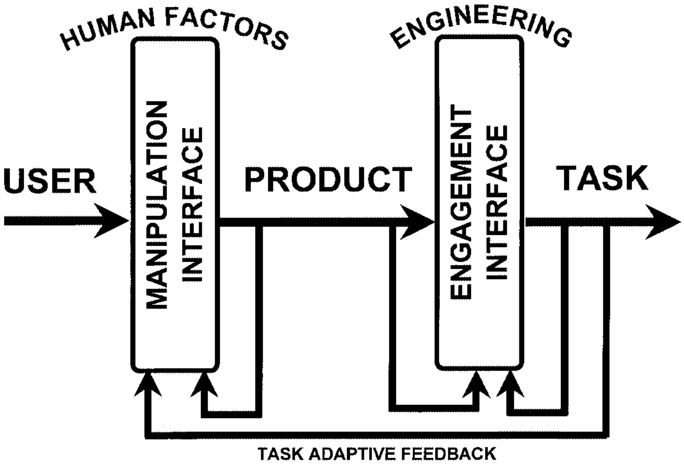


FIGURE 6.3.3 The user-product-task paradigm.

so for example, it is unwise to think that a particular design can *force* the user into some particular mode of manipulation. A simple principle follows from this observation: A product should be designed to enhance the user's ability to manipulate the product as the task demands or at the very least to not hinder the required manipulation.

Consumer-Product Matching

Designing a product for human use requires a matching of product characteristics with user characteristics. Figure 6.3.4 (adapted from Sears [5]) shows an attempt to conceptualize this matching.

The figure indicates the importance in ergonomic consumer product design of anthropometry, biomechanics, cognitive processing, functional and aesthetic valuation, and safety design.

Ergonomic Design Directives

In addition to the preceding guides, it is necessary to keep the ergonomic directives of design foremost. The ergonomic directives are outlined in Fig. 6.3.5.

This figure lists seven directives that can guide the design effort. For example, it is important to define the objectives of the design in measurable (quantifiable) terms so that any new design may be at least rank-ordered against others to determine whether it is better. If the measures are of the type that produce ratio scales, then it is possible to tell how much better one design is than another. Many engineering measures such as weight and length are ratio-scaled. Other measures such as temperature are not (100°F is not twice as hot as 50°F as is evident by converting these temperatures to centigrade, which produces a different ratio). Some of the measures may be subjective, such as user-preference ratings, and others will be objective and of the engineering type. This is usually the case for functional aspects of the design.

High Payoff Area

A particularly important directive is to find and design for the high payoff area. This is usually accomplished through skillful work with potential consumers and primarily involves

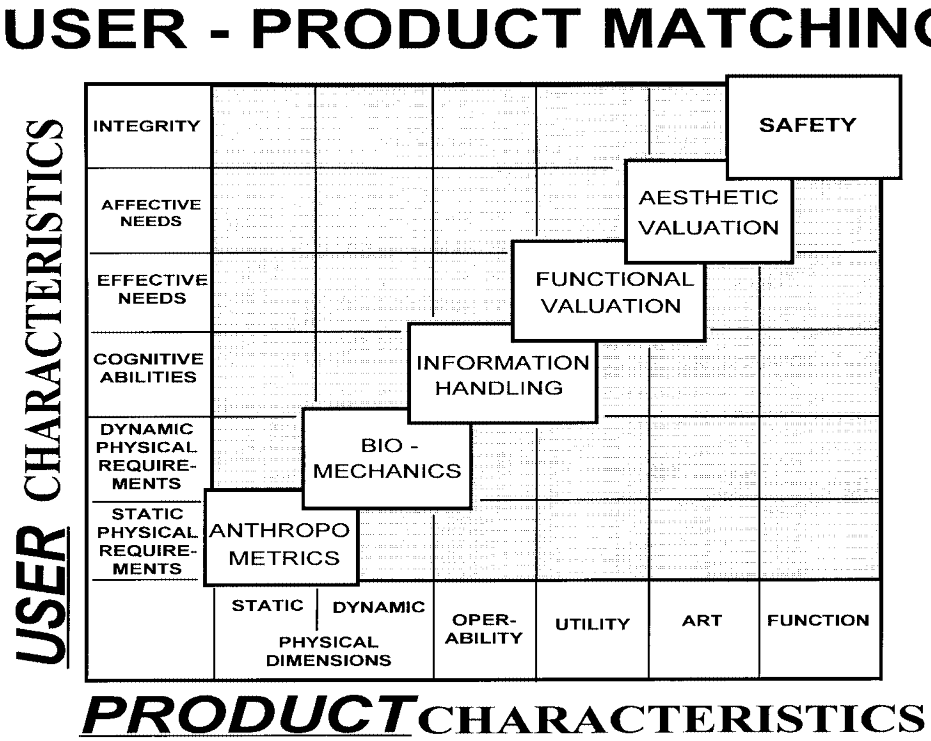

USER - PRODUCT MATCHING
USER CHARACTERISTICS
INTEGRITY
AFFECTIVE NEEDS
EFFECTIVE NEEDS
COGNITIVE ABILITIES
DYNAMIC PHYSICAL REQUIRE-MENTS
STATIC PHYSICAL REQUIRE-MENTS
SAFETY
AESTHETIC VALUATION
FUNCTIONAL VALUATION
INFORMATION HANDLING
BIO - MECHANICS
ANTHROPO METRICS
STATIC
DYNAMIC
PHYSICAL DIMENSIONS
OPER-ABILITY
UTILITY
ART
FUNCTION
PRODUCT CHARACTERISTICS

FIGURE 6.3.4 User-product matching schematic. (*Adapted from R. Sears.*)

ERGONOMIC DIRECTIVES

- DEFINE OBJECTIVES IN *MEASURABLE* TERMS
- *EVALUATE* DESIGN IN THESE TERMS
- DETERMINE THE *HIGH PAYOFF AREAS*
- DETERMINE THE *DESIGN VARIABLES*
- DETERMINE THOSE WITH THE *STRONGEST* EFFECTS
- DETERMINE THE *RELATIONSHIPS* BETWEEN VARIABLES AND OBJECTIVES
- *MANIPULATE* VARIABLES TO PRODUCE DESIRED CHANGES IN THE DESIGN

FIGURE 6.3.5 The ergonomic design directives.

using questionnaires, interviews, and focus groups. Users are rarely capable of expressing their wants and needs in design terms. The ergonomic designer must translate such expressions into design terms. Figure 6.3.6 illustrates a graphical technique called a *distorted view,* which was derived from the ratings consumers gave to the difficulty of brushing on the lingual (tongue), buccal (cheek), and occlusal surfaces in six different zones of their mouth.

A schematic drawing of the upper and lower teeth was distorted proportionally to the average difficulty rating given to each section of the mouth with the largest areas corresponding to the most difficult ratings. It is apparent from this graphic data reduction that the high payoff area is the inside back teeth and that an improved cleaning device should be designed to make it easy and effective to brush those areas. Concentrating mainly on the front teeth would be a misplaced effort because that is not where the consumer perceives his or her brushing problem to be. Attacking the wrong consumer problem results in a product that is unlikely to be successful if the consumer has a choice of other designs that accomplish the difficult portions of the task better.

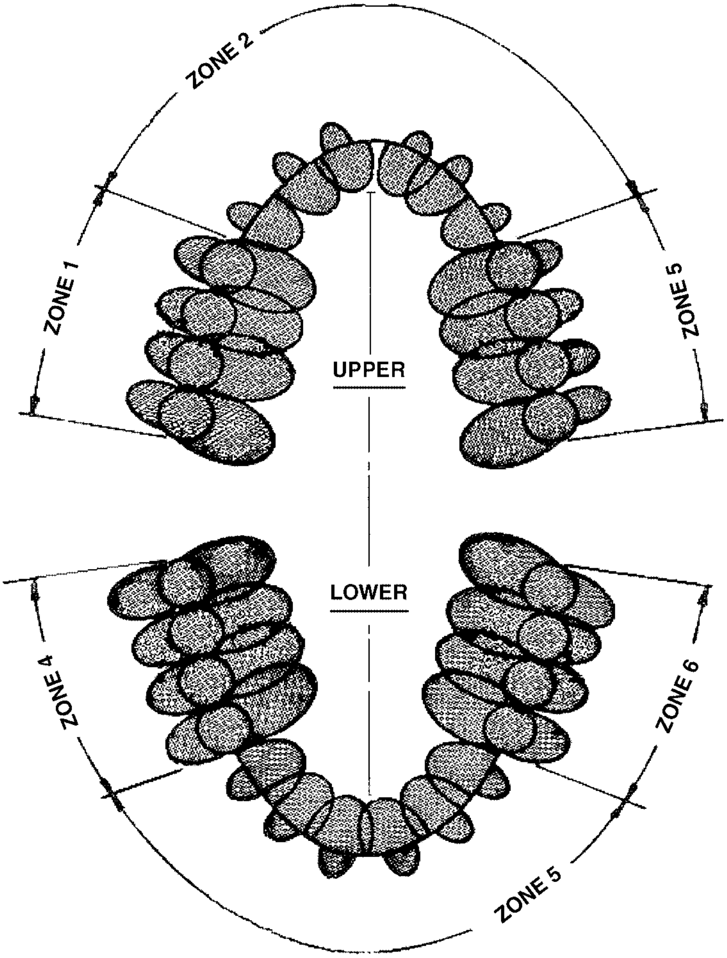


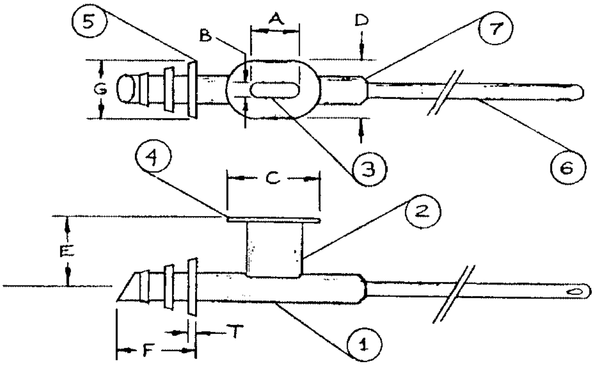
FIGURE 6.3.6 Teeth distorted according to the difficulty of brushing each area.

MORPHOLOGICAL ORDERING

Morphe from the Greek pertains to *form* and *morphology* pertains to the study of structure and form. Basically, *morphological ordering* characterizes existing solutions (products or concepts) to the problem in some systematic form. For example, if only pictures of solutions are available, as from patents, advertising copy, sales copy, and so on, or if samples of the product themselves are available, as they might be for inexpensive items, these may be grouped and regrouped in visually interesting and instructive arrangements. In his book, *Designing for People,* Dreyfuss shows a sample "pinup" of a morphological arrangement for sewing machines, which would be studied prior to embarking on a new design [6]. Every product has some functional purpose and designing it to provide all the engineering and human factors/ergonomic requirements presents a problem for the designer. A new or improved version presents similar problems. The particular power of the morphological ordering technique is that each version of a product that has been produced and is available for study can be thought of as an attempt to solve the same problem the current designer faces. Thus, systematic study of these existing solutions can often provide invaluable information that is impossible or too difficult to obtain otherwise. The following example concentrates on a selected portion of a problem and will be used to illustrate the technique and to provide a framework for emphasizing the salient points of this particular methodology.

An Example

Figure 6.3.7 shows one of many different designs for the adapter portion of a catheterizing system used in hospitals to withdraw secretions from a patient's airway. The adapter serves to couple the tube that is inserted down a patient's airway to the main vacuum source. The port (a hole that lies under the operator's thumb) in the top of the adapter allows the operator to bypass or otherwise regulate the suction in the patient's airway by covering or uncovering it. A new design to solve these problems has conflicting specifications (requirements). From an *engineering* viewpoint, the port opening should be as large as possible and the chimney height should be as low as possible to provide the lowest port resistance to airflow through this port opening in the bypass (thumb-off) position. This minimizes possible trauma to the patient's airway during insertion/withdrawal of the catheter and also permits the patient to breathe better during the bypass mode because when it is suctioning, the catheter sucks out air as well as fluids. Furthermore, the greater the residual suction at the tip of the catheter in the bypass mode, the more trauma it may cause by adhering to the lining of the airway when it is being inserted or withdrawn. Such devices are used in intensive care rooms where time is essential. However, from the *ergonomic* viewpoint, the port opening should be as small as possible to be easily covered by the smallest female thumb during the suction (fluid withdrawal) phase as well as to



1	BODY
2	CHIMNEY
3	PORT
4	FLANGE
5	CONNECTOR RIB
6	CATHETER
7	CATHETER CONNECTION

FIGURE 6.3.7 A fairly typical adapter connecting the suctioning catheter to the vacuum supply downstream.

make it easy to regulate the suction. The chimney height should be as high as possible to prevent spatter of any residual fluids from the open port during bypass, and to reduce contamination of the thumb covering the port during suction from the fluids passing beneath it. There are always counter "tugs" and "pulls" in any design, and there are often conflicting specifications developed during the initial analytical design work. In consumer product design, the engineering design requirements may pull one way and the human factors engineering design requirements may pull the other. Good design may be thought of as an optimization of design over constraints. What will be important in a new design in this case is the actual relationship between the design variables of port opening area (width and length) and chimney height, and the dependent quantity of port resistance that is to be minimized. The lower the port resistance, the less trauma caused to the patient during catheter insertion or withdrawal.

The adapters are disposed of after use, and because of the high volume of disposals, this is a good market. Because many companies want to enter this market, there are many different solutions to these problems. Figure 6.3.8 shows just 3 of many examples from patent drawings for different adapter designs. (Searching the patent literature is also an important design step. Patents exist for teaching purposes.)

By obtaining 11 different commercially available catheter adapter designs it was possible to make measurements and nonnumerical observations about color, attachments, and so forth on the products. Such data may be entered into a tabular format using a spreadsheet program so that they can be readily manipulated later. The dimensions (e.g., columns) of the table include data pertinent to the problem—in particular, the ergonomic aspects. This row (product) by column (dimensions) matrix forms the morphological chart. In a very real sense, each design alternative is an exploration of the solution possibilities and taken together the different designs span the design space to a greater or lesser degree. A new or improved design will occupy some position within this design space even if removed from the other solutions. Table 6.3.1 is an example of a morphological presentation for several adapters. (For this example, nonnumerical information, such as whether the stream flow could be seen through the adapter walls, has been omitted.)

Uses for a Morphological Chart

Once a morphological chart has been completed, a number of purposes can be supported.

1. *Location.* Each design in the table may be viewed as a point in a type of multidimensional space where the column definitions form the attributes (axis) and the particular values define a design's vector location in the space. A new design will also be located in this space using the same attributes. Its nearness to existing solutions may be computed.

2. *Statistical Analysis.* The range (high/low values), mean and standard deviation of numerical data may be computed, including the coefficient of variation (the ratio of the standard deviation to the mean), which can suggest how much variation there is to the values in any numerical dimension compared to the mean value. These statistics can help the designer understand the totality of existing solutions. In some instances, it is possible to formulate a type of average product, although the correlation between attributes requires some care in this process.

3. *Similarities and Differences.* The similarities and differences in products (solutions) may be determined. For example, it may be found that on certain dimensions, all of the values are essentially the same as indicated by a small coefficient of variation for numerical data or by similar nonnumerical features (e.g., all are transparent or angled, or colored, or noncolored). It can then be questioned whether this is attributable to pure "me-too-ism", standards, function, "tail-wags-dog" condition, ergonomics, and so on. There may be a functional basis for the similarity of some design parameter between designs because of purely physical and/or ergonomic reasons. Consumer products often accrue a large number of tail-wags-dog type constrictions as they evolve over the years from aftermarket products that accompanied the main product. For example, the holes in toothbrush holders followed the invention of

3,610,242

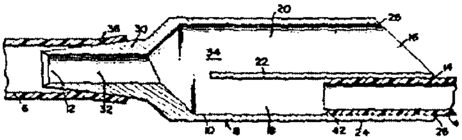
MEDICO-SURGICAL SUCTION SYSTEMS

David S. Sheridan, Argyle, and Isaac S. Jackson, Greenwich, both of N.Y., assignors to David S. Sheridan, Argyle, N.Y., by said Sheridan

Filed Feb. 28, 1969, Ser. No. 803,258

Int. Cl. A61m 1/00

U.S. Cl. 128—276 4 Claims



3,517,669

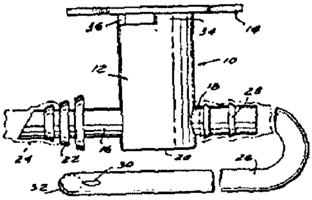
VALVED SUCTION CATHETER

Frank S. Buono, Garfield, N.J., and Robert A. Gandi, New York, N.Y., assignors to Becton, Dickinson and Company, East Rutherford, N.J., a corporation of New Jersey

Filed Mar. 12, 1968, Ser. No. 712,459

Int. Cl. A61m 1/00

U.S. Cl. 128—276 10 Claims



3,319,623

REGULATOR TO CONTROL THE FLUID FLOW OF A SUCTION CATHETER

James C. Halligan, Radburn, N.J., assignor to Becton, Dickinson and Company, Rutherford, N.J., a corporation of New Jersey

Filed Feb. 3, 1964, Ser. No. 342,146

1 Claim. (Cl. 128—276)

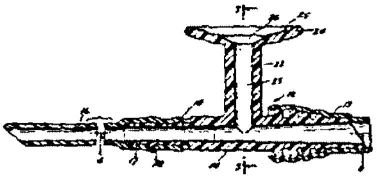


FIGURE 6.3.8 Three different adapter designs in patent drawings. (Note the different geometry of the top example.)

TABLE 6.3.1 A Morphological Chart for 11 Different Adapter Designs

	Design Attributes													
	Port length	Port width	Port area	Flange length	Flange width	Connector length	Rib large dia.	Rib width	Chimney height	Max length	Max width	Max height	Catheter connection	Port resistance
	L	*W*	*LW*	*C*	*D*	*F*	*G*	*T*	*E*	*ML*	*MW*	*MH*	*M/F*	R_{port}
Adapter	inch	inch	inch^2	inch	inch	inch	inch	inch	inch	inch	inch	inch	inch	N$^{1/2}$ sec/cm^4
BP	0.36	0.19	0.06	1	0.8	0.6	0.39	0.1	0.71	1.9	0.8	1	male	0.22
BP2	0.48	0.19	0.08	1	1.6	0.6	0.35	0.1	0.68	1.9	0.6	1	male	0.13
STD	0.35	0.35	0.1	0.71	.71	1	0.4	0.1	0.61	2.1	0.7	1	male	0.13
CT	0.47	0.19	0.08	1.08	0.63	0.8	0.36	0.1	0.71	3	0.7	1	male	0.13
CRB	0.24	0.21	0.05	0.75	0.5	0.7	0.35	0.1	0.22	2.1	0.5	0.5	female	0.29
PH	0.35	0.17	0.05	0.75	0.62	0.5	0.4	0.1	0.46	2.8	0.6	0.7	male	0.2
D	0.29	0.29	0.07	0.61	0.61	0.5	0.37	0.1	0.62	2.2	0.6	0.9	female	0.2
P	0.4	0.23	0.08	1	0.4	0.6	0.36	0.2	0.5	1.8	0.4	0.8	female	0.17
A	0.31	0.31	0.08	0.57	0.36	0.6	0.36		1	2.7	0.4	0.6	female	0.28
C	0.39	0.2	0.07			0.5	0.45	0.1	0.62	2.2	0.5	0.8	female	0.2
V	0.22	0.29	0.06	0.82	0.62	1.0	0.4		0.37	2.2	0.3	0.7	male	0.26
AVG	0.35	0.24	0.07	0.83	0.68	0.68	0.38	0.10	0.59	2.24	0.55	0.81		0.20
STD	0.08	0.06	0.01	0.18	0.37	0.17	0.03	0.04	0.20	0.40	0.16	0.18		0.06
CV	0.24	0.26	0.20	0.22	0.54	0.25	0.08	0.36	0.35	0.18	0.30	0.22		0.29

toothbrushes, but later the size of the holes in the holder began to drive the acceptable dimensions of any new brush *handle* so that it would fit existing holders, thus perpetuating a certain amount of sameness in this feature. Manufacturing processes and machinery can likewise enforce a restricted amount of flexibility in new products.

Alternatively, there may be considerable variation in a parameter among the designs as suggested by a large coefficient of variation. In this case, the designer may ask whether this variation represents an arbitrary (free) design parameter, indicating a design flexibility that can be exploited later, or if it follows from some specific reason. It may be that such a parameter is not free but rather is correlated or tightly coupled with another varying parameter. If evidence of such coupling exists, such as between length and weight (or something else more subtle), this may be a vital insight into the design. In any event, when similarities are found, the designer would want to know if this *must* be the case or if it can be changed. Likewise, if considerable variation is found, it must be determined whether this is a free or correlated design parameter.

4. *Design Niches.* A systematic study of the chart may reveal design niches or gaps that may be exploited to advantage. It might be found, for example, in examining a particular dimension or parameter such as length, which has been ordered from smallest to largest, that the values are grouped into two sets with no overlap between them: Perhaps with some product type the lengths range from 5 to 7 in and from 9 to 10 in. It can be questioned whether there is a fundamental reason for this or if the missing values represent a possible design niche for this parameter. Hunting for such possibilities is easier if the morphological data have been entered into a spreadsheet where they can be manipulated (e.g., by sorting) with relative ease.

5. *Clusters and Prototypical Designs.* It is helpful to organize the products into groups or clusters where each group contains similar designs but the groups themselves represent different designs. This type of cluster organization is particularly useful when a few representative designs are to be selected for later use. For example, it may be desired to test a trial design against others. If there are many possible contenders, as for example in a highly competitive market, it is not usually possible to make tests against all of them. Rather, a single representative or prototype sample from each cluster may be used with the expectation that the results will apply to all products within a prototype's cluster. This approach must be used cautiously because of the many, often confounding, differences even within a cluster. Experience must be used in interpreting any results. Or, one may be interested in testing or contrasting certain features (long/short, textured/nontextured, button forward/button back, etc.) represented among the designs with minimal confounding by other accompanying features. By sorting or clustering the products morphologically, such arrangements become clearer. Generally, the attempt is to form the *fewest* clusters with *maximum* difference between the clusters (representing different designs). The need to find a few representative products for use in testing, comparisons, and the like, is not any different from the need to find (from the multidimensional span of humans) a few representative types of users to serve for testing and focus groups. Clustering may be accomplished subjectively or objectively and each by various methods, but even objective techniques may reflect some subjectivity because of the (subjectively) chosen bases for forming the clusters. Three approaches to clustering are

1. *Objective analytical*—If there are numerical data to work with it may be possible to use techniques such as *cluster analysis* or *discriminant analysis* to help form clusters.
2. *Subjective intuitive*—The products can simply be sorted into different piles or clusters using one's own personal criteria. The designer's biases will naturally be evident but that will be the case wherever a subjective design decision must be made. The techniques collectively termed *multidimensional scaling* [7] can be exploited to advantage for this purpose.
3. *Consumer perceptions/product semantics*—Products "speak" to a consumer via their sensory (usually visual) language and some of this language reflects and derives from humans through the process of design. Given a set of products to sort or categorize, there should be

little difficulty in sorting beds into one pile and hair dryers into another (and everything else into a third). In any case, studying the sorting results will provide valuable insight into user perceptions about the products.

6. *Correlational Analysis.* Many aspects of a design, particularly pertaining to functional or satisfaction measures, depend in subtle and complex ways on a number of different product design parameters. Usually, the problem of determining this relationship is much too complicated to yield to analytical modeling means. However, when a sufficiently large number of different product designs actually exist (which is often the case with consumer product design in a highly competitive product area), determining relationships between design variables and functional or satisfaction measures may be derived from a correlational approach based on the morphological chart data. This is usually possible when the existing designs ordinarily exhibit sufficient variation in the relevant design parameters. If consumer reaction to the different designs is available, (e.g., like, don't like) it may be entered into the table and correlations between the reactions and the design variables looked for. The correlational type of analysis will be illustrated in the following case study.

A CASE STUDY—CORRELATIONAL DESIGN ANALYSIS OF AN ADAPTER FOR AN AIRWAY CATHETER USING THE MORPHOLOGICAL APPROACH

In the example of Fig. 6.3.7, there are measurements pertaining to achieving engineering as well as ergonomic goals. The performance measure here is *cross-suctioning effectiveness,* which is the ability of the adapter to relieve the suction at the tip of the catheter when the port is open by having as low a port resistance to airflow as possible. The design directive is to locate those design parameters that have the greatest effect on the functional requirement (cross-suctioning effectiveness) and manipulate them to produce the best functional and ergonomic results.

Correlational Model

Using the data from Table 6.3.1, a correlational model was derived relating the dependent variable of port resistance to the design parameters of port length, port width, and chimney height, which were three variables reasonably anticipated to determine port resistance. Port resistance to airflow was determined for each adapter by actual airflow measurements. These results are also shown in Table 6.3.1 as port resistance (R_{port}) measured as ($N^{1/2}$ sec/cm^4). One simple approach to developing a mathematical model of the relationship between R_{port} and the design variables is to hypothesize an equation expressing port resistance (R_{port}) as a linear function of chimney height (H) and port area opening variables (L, W) where L is the length of the opening parallel to the stream flow and W is the width of the opening perpendicular to this flow. Such an equation is shown in Eq. (1):

$$R_{port} = k + aH + bL + cW \qquad (1)$$

To meet the conflicting design requirements alluded to previously, the designer must know how sensitive the port resistance is to each of the design parameters (H, L, W). The values (k, a, b, c) can be determined by multiple linear regression analysis. If the agreement between the values from Eq. (1) and the actual values is not satisfactory, the expression between R_{port} and H, L, and W can more faithfully represent the physics of the problem such as in Eq. (2) where nonlinear regression analysis is applied.

$$R_{port} = kH^a/L^bW^c \tag{2}$$

Linear regression can still be used in Eq. (2) by taking the logarithm of both sides resulting in an equation that is linear in the parameters. Equation (1) and linear regression yielded the result:

$$R_{port} = 0.57 + 0.14\,[\text{chimney height}] - 0.92\,[\text{port length}] - 0.57\,[\text{port width}] \tag{3}$$

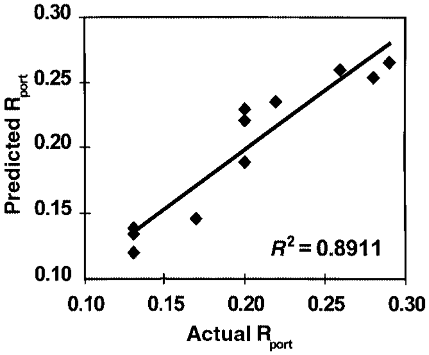


FIGURE 6.3.9 Agreement between actual and predicted port resistance for 11 different adapter designs.

This equation predicts the actual measured values of R_{port} in the table remarkably well ($r^2 = 89\%$) and extremely well for several later experimental designs ($r^2 = 96\%$) where tolerances and designs could be controlled better. The set of adapters in the morphological chart includes the one shown at the top of Fig. 6.3.8, which has a significantly different geometry from the common *T* shapes of the other ones entered into the table. Figure 6.3.9 shows the actual versus predicted port resistance for the 11 adapters.

It can be seen that the prediction is quite good. It would have been impossible to obtain such accuracy by a mathematical model of an adapter's airflow resistance starting from air/fluid mechanics considering problems such as airflow turbulence. The utility of the results can now be used in a new design. For example, Eq. (3) indicates that port length (L) has the strongest effect on tip suction and chimney height (H) the least. For example, doubling the port length decreases the port resistance by about 70.0 percent, while doubling the chimney height increases it by 15.0 percent. Thus, increasing chimney height by about 10 percent to decrease contamination through spatter would lead to only a 2 percent increase in port resistance, and this could be easily offset by a 1.2 percent increase in port length, a 2.3 percent increase in port width, or of course much smaller increases of both L and W if both are changed. These dimensions for the port opening can then be checked against anthropometric data for thumb sizes of the appropriate user population (female) anticipated to be the operators of the device.

Although it is not wise to extrapolate too far outside the range of values, experience has shown that this is feasible to some extent without making a large error in the actual results.

CONCLUSIONS

Having a multiplicity of product versions to study can provide vital design information regarding the relative importance and sensitivities of the relevant design parameter. The power of the morphological approach arises from the "spanning" of the design variable values produced by the different existing designs. Each one can be viewed as a free experiment and the results used for a new design. Studying existing designs is an important step in targeting a new design in an efficient fashion.

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BIOGRAPHY

John Kreifeldt is a full professor of engineering design in the mechanical engineering department of Tufts University in Medford, Massachusetts. He began his interest and study of human factors at UCLA in 1959 (B.S.), continued study at M.I.T. (M.S., E.E.), and at Case Western Reserve University (Ph.D.). He is cofounder and engineering head of the interdisciplinary undergraduate program in engineering-psychology (initiated 1972) and founder and head of the master's and doctoral programs in human factors in the engineering college. He specializes in consumer product design and has served as consumer product design consultant to legal firms, industries, and U.S. government agencies. He holds several patents and is codesigner of the REACH© toothbrush and other consumer products.

Source: MAYNARD'S INDUSTRIAL ENGINEERING HANDBOOK

CHAPTER 6.4

MANUFACTURING ERGONOMICS

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This chapter will discuss the key factors that affect the manufacturing workplace in the area of *ergonomics*. Ergonomics literally means *the study of work*. It examines the physical interaction between the worker and the work environment, including such factors as machinery, the workstation, climate, and other factors. If the match between the worker and work environment is poor, the worker's ability to perform the job will be severely compromised. Over the short period of time, this poor match may lead to fatigue and worker discomfort. If adverse conditions persist, physical injury and disability may occur. Even before health effects show up in medical records, poorly designed jobs can affect employees and company operations. Improper job design hinders the worker's ability to perform at peak efficiency and to produce high-quality parts. It also results in increased absenteeism and decreased job satisfaction.

INTRODUCTION AND BACKGROUND

Ergonomics can be defined as the study of work. Chaffin and Andersson [1] further define ergonomics as *fitting the work to the person*. The primary goal of ergonomics is "improving worker performance and safety through the study and development of general principles that govern the interaction of humans and their working environment." Rohmert [2] states that ergonomics "deals with the analysis of problems of people in their real-life situations." Further, he urges that ergonomists "design these relations, conditions and real-life situations with the aim of harmonizing people's demands and capacities, claims and actualities, longings and constraints."

Ergonomics is concerned with the problems and processes involved in designing systems and processes for effective human use, and in creating environments that are suitable for human living and work. Figure 6.4.1 illustrates how the relationship or "fit" between the worker and the workplace is defined by how the worker interacts with the workplace through tools and controls and how the workplace provides information back to the worker through displays or other instruments.

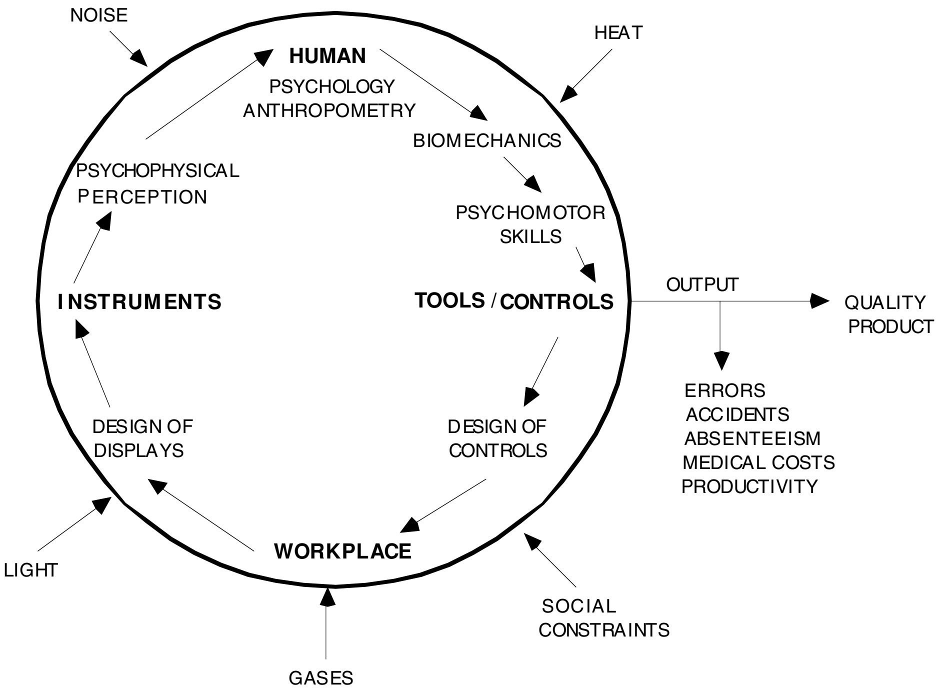

NOISE
HEAT
HUMAN
PSYCHOLOGY
ANTHROPOMETRY
BIOMECHANICS
PSYCHOPHYSICAL
PERCEPTION
PSYCHOMOTOR
SKILLS
INSTRUMENTS
TOOLS / CONTROLS
OUTPUT
QUALITY
PRODUCT
ERRORS
ACCIDENTS
ABSENTEEISM
MEDICAL COSTS
PRODUCTIVITY
DESIGN OF
DISPLAYS
DESIGN OF
CONTROLS
WORKPLACE
LIGHT
SOCIAL
CONSTRAINTS
GASES

FIGURE 6.4.1 Interface between the human and workplace.

Properly designed workplaces, equipment, facilities, and tools can

- Reduce occupational injury and illness
- Reduce worker's compensation, sickness, and accident costs
- Reduce medical visits
- Reduce absenteeism
- Improve productivity
- Improve product quality and reduce scrap
- Improve worker comfort on the job

Ergonomics can enhance the traditional industrial engineer's work measurement process by blending traditional time study information with health, safety, and worker capability data into a seamless measure of the contemporary workplace. Final productivity figures are often based on the data collected from time measurement studies and on the negotiation process between management and the worker representative. On the other hand, health, safety, and worker capability data are based in measurement of human performance in the workplace and in the laboratory. The ergonomist uses this data to identify elements of the job that reduce the quality of the interface between the human operator and the workstation. A poor interface can cause unnecessary stress to the operator, leading to an increased risk of injuries or an increased risk of errors (which may lead to an accident, poor product quality, or a loss in productivity).

In order to measure stress on the human body, the relationship between disease and exposure must be understood. This relationship is determined through analysis of various exposures and their effect on a target population through epidemiological studies. Measuring ergonomic stress is somewhat similar to collecting an air sample for toxins. Measuring ergonomic exposure, however, cannot be accomplished by simply determining the concentration of a toxin on a collection medium. An ergonomic analysis must include measurements of the environment, assessment of fatigue, and biomechanical modeling. Through this information, the analyst can *then* review the exposure data and attempt to quantify it into levels of ergonomic risk.

Ergonomic analysis often deals with two areas—*psychological* and *physiological* elements. Psychological ergonomics deals with the match between the human and workplace from an information processing viewpoint. These activities often manifest themselves during inspection tasks or during various machine operation tasks (e.g., control and display operation). On the other hand, physiological ergonomics refers to exposures that affect the operator through mechanical processes (biomechanics) or metabolic processes (fatigue).

This chapter provides a brief overview of key factors that affect the manufacturing workplace in the area of ergonomics.

MANUFACTURING ERGONOMICS—RISK AND CONTROL

In many cases, ergonomic analysis looks at how the physical design of a particular workstation may affect human performance. In the area of biomechanics, ergonomic analysis often deals with three distinct types of work or activities: (1) work involving *manual handling* of objects; (2) work involving *assembly and/or disassembly;* and (3) work involving *machine operation.*

The human body can be thought of as a sophisticated mechanical system. The bones provide a framework to support the various loads on the body. The muscles provide the power to move the frame about the joints through muscle contraction. Tendons attach bone to muscle and convert the muscle contraction to mechanical energy. As muscles contract, the tendons pull the bone around the axis of the joint like a pulley.

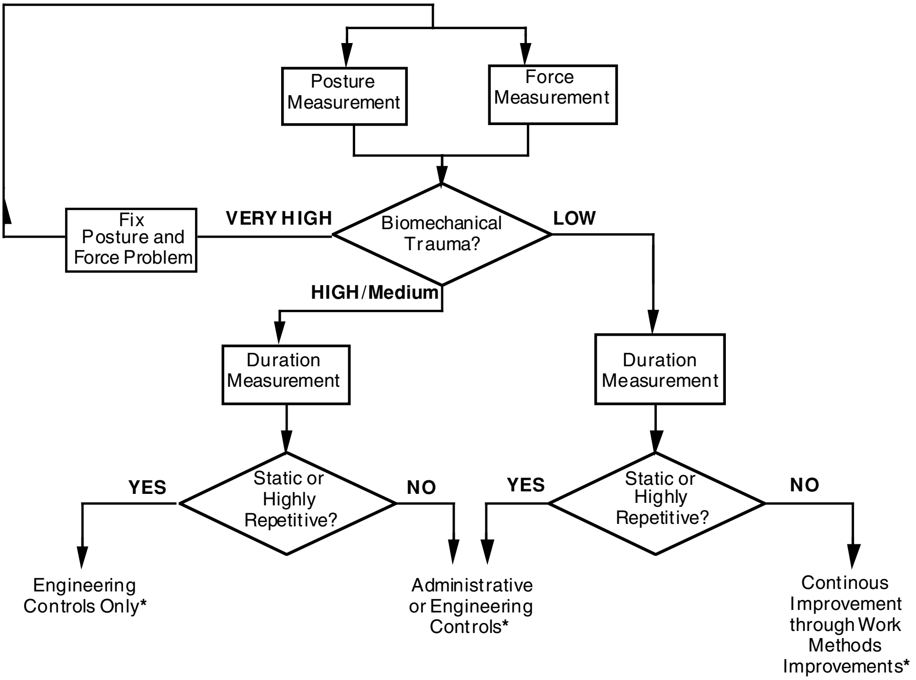
The three main generic occupational risk factors associated with ergonomic stress are *force, frequency,* and *stressful postures.* Independently, each factor can lead to ergonomic stress if it exceeds human capability limits. However, combinations of these factors may lead to physical harm even if the independent levels of each risk factor are at or below their individual human capability limits.

- *Force* can be defined as the amount of work that the muscles, tendons, joints, and adjacent tissues must do in order to perform a particular action. The force exerted often depends on a variety of factors, including posture, weight, and friction.
- *Frequency,* often referred to as *repetitiveness,* is a measure of the time required in specific postures. Depending on the amount of force or the type of posture, repetitiveness can be harmful if repeated many times or if held for sustained periods of time.
- *Stressful postures,* when sustained or used repeatedly, can be harmful to the musculoskeletal structure, especially when force is exerted. There are many stressful postures, usually described by body part.

Figure 6.4.2 shows a simple decision tree that is useful for identifying potential physiological ergonomic stress. This decision tree can be translated into three basic questions that engineers need to ask before designing jobs:

1. Is the population at risk strong enough to do the job without getting hurt? This question addresses the instantaneous risk that a person may encounter in performing the job once. The resulting injury is typically biomechanical (strains or sprains) in nature.

2. Is the population at risk strong enough to do the job long enough, and is there enough recovery time to do it again? This question addresses the risk encountered performing the job over a period of hours, days, or weeks. The risk often manifests itself as local or whole-body fatigue and/or as biomechanical trauma.


Posture Measurement
Force Measurement
Fix Posture and Force Problem
VERY HIGH
Biomechanical Trauma?
LOW
HIGH/Medium
Duration Measurement
Duration Measurement
YES
Static or Highly Repetitive?
NO
YES
Static or Highly Repetitive?
NO
Engineering Controls Only*
Administrative or Engineering Controls*
Continous Improvement through Work Methods Improvements*

* **Before Making Job Changes, Check for:**
Mechanical Stress Concentrations
Temperature Extremes (either whole-body or locally)
Vibration Exposures (either whole-body or segmental)

FIGURE 6.4.2 Ergonomic decision tree for biomechanical stress (force/posture and repetition).

3. If the job is repeated often enough for an extended period of time, will the population at risk contract cumulative damage? The current state of the science does not allow an accurate assessment of this question. However, because of the high correlation between questions 1, 2, and 3, reducing risk in 1 and 2 will result in substantial reduction in risk for 3.

Activities Involving Manual Handling of Objects

Fatigue. Fundamental to the concept of physical stress is fatigue. Whenever a machine performs work, energy is required. This might be in the form of electrical power, or could be gasoline or some other fuel if an internal combustion engine is used. Similarly, when the human body performs work, energy is also required. The muscles in the body are the "engines," and the "fuel" is the product of a complex chemical conversion process (metabolism) of the food that we eat. This fuel is supplied to the muscles by the cardiovascular system. When the muscles are active and demand more energy resources than can be supplied, fatigue results.

There are two basic types of metabolism used by the body. One requires oxygen in the process and is known as *aerobic* metabolism. The other does not require oxygen and is known as *anaerobic* metabolism. The anaerobic process is much less efficient than the aerobic process, but it is usually the first source of energy used by the muscles when the cardiovascular system has not yet had enough time to respond to the muscles' needs with blood flow containing foodstuffs and oxygen to support their activity. There are also two basic types of fatigue experienced by the body. One is *localized muscle* fatigue and the other is *whole-body* fatigue. Localized muscle fatigue is often associated with the anaerobic process and is limited to a particular muscle group that has undergone a sustained (static) exertion or a very repetitive series of exertions with little or no rest. Whole-body fatigue is usually associated with aerobic metabolism and the inability of the person's cardiovascular system to supply enough food and oxygen to meet the energy expenditure rate demand of the working muscles throughout the entire body.

Description of Localized Muscle Fatigue. The oxygen supply (via blood flow) to a muscle is usually sufficient to support aerobic metabolism during moderate activity. However, higher levels of activity may lack sufficient blood flow for aerobic metabolism to produce ATP (adenosine triphosphate) and to carry away anaerobic metabolism waste products. As anaerobic metabolism continues, lactic acid accumulates, foodstuffs in the muscle become depleted, needed ATP levels cannot be maintained, and muscle fatigue develops. For maintenance of muscle contraction without fatigue, sufficient oxygen must be present for aerobic metabolism of ATP.

The mechanical action of muscle contraction actually restricts blood flow through the muscle and forces anaerobic metabolism. Figure 6.4.3 displays the increase and then decrease in blood flow as grip contraction increases. Figure 6.4.4 illustrates that as a muscle is contracted toward its maximum strength, the endurance of its contraction decreases because of the development of localized fatigue. As muscle contraction increases above about 20 percent of its maximum voluntary contraction (strength), blood flow (and the corresponding oxygen supply) falls below muscle demand, requiring further anaerobic metabolism and shortening endurance time.

In general, sustained or highly repetitive, forceful muscle contractions approaching or exceeding 20 percent of maximum muscle strength limit the flow of blood to the contracting muscle, resulting in local muscle fatigue and discomfort. Over time, this fatigue will diminish a worker's ability to perform a certain function job.

Control of Localized Muscle Fatigue. Control of localized muscle fatigue can be achieved by designing the work to reduce the required sustained muscle contractions, or by periodically providing periods of rest between periods of potentially fatiguing work. Workplace design and task specifications should limit sustained contractions requiring over 20 percent of expected muscle strength.

Static loading of muscles is a common cause of localized muscle fatigue. The act of constant contraction (even at low exertion levels) with no relaxation does not allow enough blood to

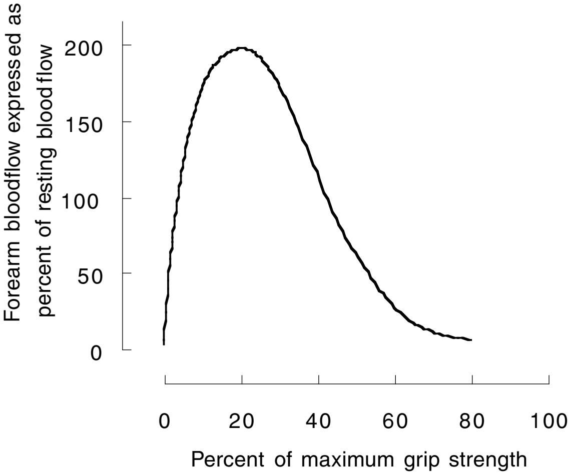


FIGURE 6.4.3 Muscle blood flow versus static contraction level. (*Adapted from Armstrong.*)

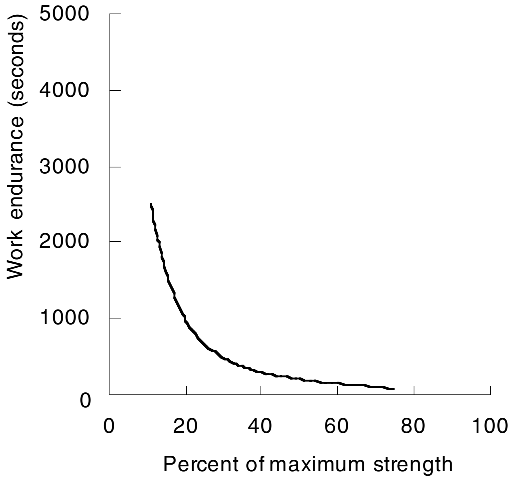


FIGURE 6.4.4 Static endurance time versus load held (expressed as a percent of maximum strength).

flow through the contracting muscles to prevent localized fatigue. A common example of this would be maintaining a stressful posture for a prolonged period of time, such as holding the arms outstretched in front of the body or bending the neck during prolonged use of a video display terminal. Careful attention to the presentation angle of the work can help to reduce localized neck and shoulder fatigue.

Scheduling periods of rest between work (muscle contraction) periods allows muscles to recover from the effects of contraction. This approach can be accomplished by adjusting work content and/or directly providing rest periods during the shift. The work design goal would be to avoid fatigue through adequate rest periods for the affected muscle group for the level of exertion required.

Description of Whole-Body Fatigue. Dynamic movements such as walking, load carrying, and repeated load lifting utilize many different muscle groups simultaneously. Unlike static loads or sustained postures, the muscles involved often allow enough blood flow to keep localized muscle fatigue from occurring. However, these dynamic activities requiring many active muscles groups can require large energy expenditures from the body as a whole. When the metabolic energy expenditure rate demand exceeds the body's energy-producing capability (the work capacity of the individual), whole-body fatigue develops.

Whole-Body Response to Energy Demands. Like static muscle exertions, dynamic exertions require oxygen and foodstuffs. As the activity increases, so does the metabolic demand of the muscles. The body responds to this increased energy demand in several ways. The rate of respiration (breathing) increases to bring more oxygen into the body through the lungs to support aerobic metabolism. The heart rate increases to circulate more blood to carry the oxygen from the lungs and foodstuffs to the working muscles and also carry away metabolic byproducts from the muscles. One of the by-products of aerobic metabolism is heat. Therefore it is likely that the person will begin to perspire and that there will be an increase of blood flow to the skin—both of which are mechanisms for dissipating internal body heat. If the environmental factors are also contributing excessive heat, then a heat-stress situation may occur. The whole-body energy expenditure rate of aerobic activities is linearly related both to the amount of oxygen used by the body (oxygen uptake) and to the heart rate. Hence, it is possible to estimate the energy requirements of a dynamic task or job from the oxygen consumption rate or heart rate, though the latter is much less precise.

Skeletal muscles can contract even in the absence of oxygen by using anaerobic metabolism. The respiratory and circulatory systems normally require two to three minutes to increase their output in response to increased metabolic demands. During this time, anaerobic metabolism takes place, causing an *oxygen debt,* which must be repaid when the muscle activity ceases. Hence the heart and respiratory rates do not drop back to normal immediately upon cessation of work, but gradually decrease while paying back the debt incurred in the anaerobic start-up of the muscle activity. Figure 6.4.5 illustrates this relationship. When aerobic metabolism produces enough energy to satisfy ongoing muscular needs, the body is considered to be in the *steady state.*

Figure 6.4.6 illustrates the linear relationship between increasing energy expenditure rate and increasing heart rate for well-trained people. The *maximum physical work capacity* (MPWC), often called the *aerobic capacity,* is the maximum energy expenditure rate that can be attained by an individual. This maximum level of activity can only be maintained for about four minutes. Energy expenditure rates are often expressed in terms of *kilocalories per minute.* A kilocalorie (kcal), a unit of energy, is the measure referred to when discussing how many "calories" are contained in the food we eat. This rate is usually limited by the maximum heart rate and fitness level of the individual. Figure 6.4.6 shows that the maximum work capacity is reduced for tasks with static work elements that involve anaerobic metabolism. Most work tasks contain a combination of aerobic and anaerobic activities.

Age affects the maximum heart rate and hence an individual's MPWC. This is especially important when considering today's aging workforce. The decline with age of the maximum heart rate for both sexes can be roughly estimated by the function [3]:

$$\text{Maximum heart rate} = 220 - \text{age (in years)}$$

For example, a 35-year-old person would have a predicted maximum heart rate of 220 – 35 = 185. This relationship can be useful in estimating an individual's aerobic capacity with submaximal testing procedures.

The average MPWC for the female population is less than that of the male population, although there is considerable variability between individuals based upon many factors, including fitness level. The more physically fit an individual is, the higher the MPWC is likely to be. For job design purposes, common values often assigned to MPWC are 16 and 12 kcal/min for normal, healthy men and women, respectively. It is also generally recognized that individuals should not be expected to exceed 25 to 33 percent of their MPWC for eight hours of continuous work. Work above these levels may lead to whole-body fatigue. Using 33 per-

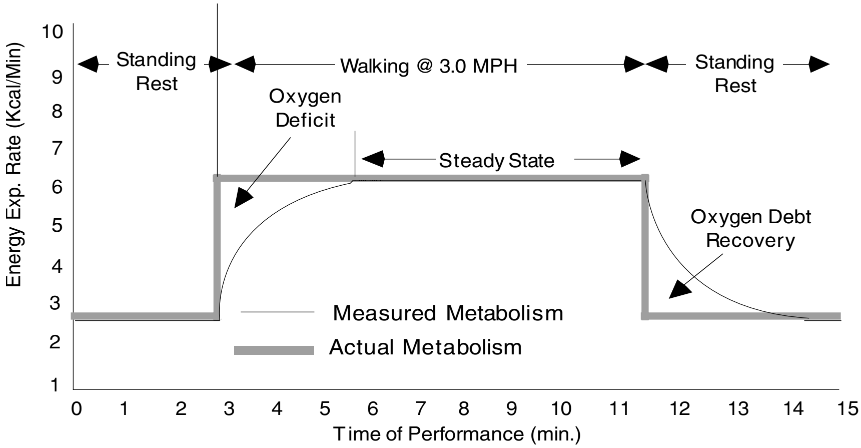


FIGURE 6.4.5 Diagram showing an example of energy expenditure over time and the oxygen debt and recovery periods.

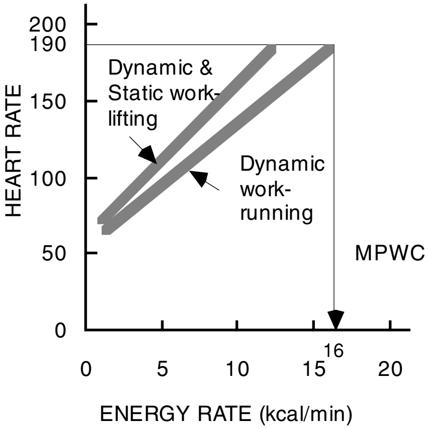


FIGURE 6.4.6 Representative relationship between heart rate and maximum physical work capacity (MPWC). For the situation given above, a person with a maximum heart rate of 190 would have a MPWC of 16 kcal/min for highly dynamic work.

cent of MPWC as the benchmark, common design goals for eight-hour jobs are therefore 5.3 kcal/min for healthy male and 4.0 kcal/min for healthy female populations. It must be recognized that not all workers will fit these "healthy" categories, and that these energy expenditure rates levels will be strenuous for some individuals. Consequently, the National Institute of Occupational Safety and Health (NIOSH) recommends design limits of 5.0 kcal/min and 3.5 kcal/min for men and women, respectively [4].

Physical work capacity (PWC) is a measure of the recommended energy expenditure rate for a specific duration of time and is dependent on MPWC. As just noted, MPWC is dependent on physical fitness. In the absence of information of the physical fitness of a specific individual or population MPWC can be estimated as function of age. The work of Bink [5] and Bonjer [6] was modified by Chaffin [7] to allow the estimation of the PWC, for an individual as a function of the age and the duration of the intended work. Table 6.4.1 illustrates the PWC for males and females as a function of age for work durations of 2, 4, 8, and 8.5 hours. This can be compared to the estimated job energy expenditure requirements discussed in the next section to determine expected level of metabolic stress for an individual or population.

Estimating Job Energy Expenditure Rate Requirements. Four methods are commonly used to determine the metabolic requirements of specific jobs:

1. Actual measurement of oxygen consumption of a worker while performing the job
2. Macrostudies (table values and job classifications)
3. Predictive macrostudies (job attribute energy summation)
4. Predictive microstudies (elemental work-task energy summation)

Method 1, the direct measurement of oxygen consumption, can be achieved by measuring expiratory ventilation (liters of air expired per minute) and expiratory air oxygen content (the fraction of oxygen in the expired air). For the average individual, the conversion factor between oxygen consumption and energy expenditure is 4.9 kcal/liter of oxygen used. This method requires the worker to wear a face mask to collect expired respiratory gases, and sometimes other equipment that can alter the person's work method and affect the analysis results. This method is most often used in the laboratory.

Several macrostudies (method 2) have been performed to determine the energy expenditure of people performing different jobs. They are typically displayed by job description and energy exposure rate for a particular population (e.g., male/female, weight). These are considered *macro* because the many tasks that comprise the entire job are "lumped" together and a single energy expenditure value is assigned to the job. Since there is often little or no standardization of job titles that would allow a direct comparison of table values to a specific job, this data has limited usefulness for the analysis of manufacturing jobs.

TABLE 6.4.1 Physical Work Capacity (PWC) in kcal/minute for Females and Males as Function of Age and Work Duration

Females				
Age (yrs)	120 min	240 min	480 min	510 min
20	7.26	5.86	4.46	4.34
25	7.07	5.71	4.35	4.23
30	6.82	5.51	4.20	4.08
35	6.26	5.05	3.85	3.74
40	5.94	4.80	3.66	3.56
45	5.82	4.70	3.58	3.48
50	5.69	4.60	3.50	3.41
55	5.51	4.45	3.39	3.29
60	5.19	4.19	3.19	3.11
65	4.94	3.99	3.04	2.96
Males				
Age (yrs)	120 min	240 min	480 min	510 min
20	9.68	7.82	5.95	5.79
25	9.43	7.61	5.80	5.64
30	9.09	7.34	5.59	5.44
35	8.34	6.74	5.13	4.99
40	7.93	6.40	4.88	4.74
45	7.76	6.27	4.77	4.64
50	7.59	6.13	4.67	4.54
55	7.34	5.93	4.52	4.39
60	6.92	5.59	4.26	4.14
65	6.59	5.32	4.05	3.94

A more useful macro analysis procedure was developed through research sponsored by the Motor Vehicle Manufacturers Association (MVMA) [8]. This method uses a simple job classification system to "predict" different levels of energy use. The classification system is outlined in Table 6.4.2.

A simple method for predicting energy expenditure was also developed through a research project sponsored by the MVMA. This approach, referred to as *predictive macrostudies* (method 3), is more accurate than the previous model, but is a little more difficult to use. The degree of accuracy this model achieves will be satisfactory for most analyses. The formula for the model is:

$$\text{Metabolism (kcal/hour)} = 117 + (25 * \text{Arms}) + (2.1 * \text{Walk}) + (4.4 * \text{Lift}) \\ + ([5.2 + (2.2 * \text{PForce})] * \text{Dist})$$

TABLE 6.4.2 Values of Metabolism (kcal/hour) for Different Combinations of Job Classifications

Arms*	Weight†	Walk‡	
(>0.5 m)	(>5 kg)	(>5m or 16 ft in 1 min)	
(>20 in)	(>11 lb)	**No**	**YES**
NO	—	**140**	**175**
YES	**NO**	**175**	**230**
	YES	**230**	**295**

* Most of the hand motion exceeds an envelope of 0.5 meter (20 in).

† Weight of parts/tools handles or sustained force applications for pushing or pulling are greater than 5 kg (11 lb).

‡ Person walks, pushes, and/or pulls more than 5 meters (16 ft) in a one-minute period.

where:
Arms 0: Little hand/arm movement
1: Hand movement mostly within a 0.5 meter (20 in) zone
2: Hand movement frequently outside a 0.5 meter (20 in) zone and no other body movement involved
3: Whole body involvement (bend, extended reach, stoop, etc.)
Walk X: Distance for walking or carrying per 1-min in meters (feet/3)
Lift X: Product of values for arms, weight, and frequency
Arms Same as above
Weight 1: Units handled less than 2 kg (4.4 lb)
2: Units between 2 kg (4.4 lb) and 5 kg (11 lb)
3: Units handled greater than 5 kg (11 lb)
Frequency 1: Work cycle less than 2 cycles/min
2: Work cycle between 2 and 5 cycles/min
3: Work cycle greater than 5 cycles/min
PForce X: Force sustained during push/pull in kilograms (pounds/2.2)
Dist X: Distance of push/pull per 1-min in meters (feet/3)

The last method (4) predicts metabolic energy expenditure rates by summing up the energy requirements of small, well-defined work tasks that comprise the entire job and the postures assumed by the worker during the performance of these tasks. The resulting estimate is much more precise than a single table value depicting an entire job. The required job analysis procedure is accordingly more tedious, but computerization has made this type of analysis feasible. This method allows energy expenditure analysis of existing jobs as well as simulated, nonexistent jobs. This ability to simulate workplaces is important in the job design process. This method also identifies specific work tasks that contribute heavily to a high overall job energy expenditure rate, which facilitates job redesign activities. For more information on this important method, please refer to Garg [9].

Job Design to Reduce Whole-Body Fatigue. In order to design jobs to minimize the energy required, high-energy tasks must be recognized. In general, whenever large muscle groups are employed, large amounts of energy will be needed. High-strength exertions also require large amounts of energy. Highly repetitive exertions such as these obviously require high amounts of energy. More specifically, the metabolic rate is highly influenced by the weight of the load handled, the vertical location of the load at the beginning of the lift, the vertical lift distance traveled, the lift frequency, the walking distance, and the load-carrying distance. Control of these variables can be achieved by altering the design of the workplace according to the following principles:

1. Avoid lifting objects from the floor when doing so will require squatting or stooping. Attempt to locate the origin of the lift close to the knuckle height of the worker.
2. Minimize the vertical distance one must lift an object.
3. Minimize walking and carrying distances.
4. Reduce the frequency of high-energy tasks where possible.

Care must be taken in the trade-off between lift frequency, size of the load lifted, and walking distance. Even though it appears beneficial to increase the load weight to reduce lifting frequency, lifting the increased load might be stressful to the lower back. There is no best answer to this trade-off dilemma, and each situation must be handled individually. Obviously, it would be best to minimize both the load and the frequency, but this is often not possible without mechanical assists or a complete job redesign.

Administrative Controls to Reduce Whole-Body Fatigue. If it is not possible to redesign a job to reduce its overall energy requirements to acceptable levels, administrative controls should be applied to reduce the risk of whole-body fatigue for workers. These controls can take the form of careful work/rest cycling and/or individual fatigue monitoring that accounts for individual maximum physical work capacity (MPWC) or aerobic capacity. In either case, the job should be redesigned to reduce its energy expenditure requirements, or another worker with an aerobic capacity (and subsequent physical work capacity) high enough to prevent excessive fatigue should be selected to perform the job.

A note about "proper" lifting technique: Although training programs for lifting tend to emphasize the squat lift technique (e.g., bending with the knees rather than the back), this method can place high stresses on the knee joints and thigh muscles, and may require as much as twice the energy demands of freestyle lifting. Consequently, because freestyle lifting requires less energy, workers who do a lot of lifting will tend to use the freestyle method even though it may place higher stress on the lower back. Redesigning the workplace to eliminate low back risk factors will generally have better results in reducing injuries than teaching proper lift techniques.

The relationship of lift technique to back injury may be more dependent on the size of the object than on how it is lifted. When objects are large and cannot be held close to the body during lifting, the compressive forces on the spine will be high, regardless of whether workers are bending or squatting to lift. The next section shows how to quantify biomechanical stress to the musculoskeletal system during manual material handling tasks.

Back Pain and Biomechanics. Every year, over 2.5 million low back injuries and 1.2 million disabling low back injuries were occurring each year in the United States, and low back pain was the diagnosis of 10 percent of all chronic health conditions [10,11]. An average 28.6 workdays per 100 workers with low back pain were lost for each case of low back pain [12].

The overall cost for low back pain has been estimated to be between $4.6 and $11 billion per year [13]. This cost represents a tremendous loss in productivity, as measured in dollar output per worker, and extremely high levels of human suffering. Anything that can be done to minimize the risk factors and so to reduce the associated incidence of disease will greatly reduce human suffering and costs to industry.

Function and Structure of the Spine. The spine serves as the main structure of the human body. It serves, among other things, to maintain body posture, provide a lever arm for lifting, and support the internal organs.

The spine is mainly composed of bony vertebrae held together by ligaments and supported by muscles. The major components are (see Fig. 6.4.7): the erector spine muscles, which serves to support the back and provide a power mechanism to lift; the vertebral body, which serves to provide mechanical support and strength; the facet joints, which are attached to the vertebral body and serve to interconnect the vertebrae of the spine; and the intervertebral disks, which act as shock absorbers and counteract compressive forces on the spine.

The spine is divided into four sections: (1) cervical—the upper 7 vertebrae that are located in the neck; (2) thoracic—the 12 vertebrae located below the cervical region in the trunk; (3) lumbar—the next 5 vertebrae located in the low back; and (4) sacrum/coccyx—the final set of fused vertebrae, commonly referred to as the tailbone.

Much of the work in ergonomic modeling and human factors concerning the back deals with the lower spine, specifically the area between the fifth lumbar vertebra and the first sacral vertebra (L5/S1). This region was chosen because of statistical data regarding back disorders.

Industrial Risk Factors. Manual exertions associated with lifting tasks can require excessive strength. Recent studies have shown that the risk of musculoskeletal injuries (e.g., strain, sprains, and back pain) increases when the strength demands of a task exceed the strength capabilities of a worker. These studies also have shown that the risk of low back pain increases when the magnitude of the compressive forces acting on the L5/S1 spinal disk exceeds a threshold level of 770 pounds [14–16].

Several workplace factors have been shown to contribute to low back pain. These variables are separated into two groups: (1) personal characteristics and (2) task, object, or workplace characteristics. Personal characteristics include age, gender, anthropometry, muscle strength, previous medical history, fatigue, trauma, socioeconomic and emotional status, personality, congenital defects, and genetic factors [16,17]. Workplace factors associated with low back

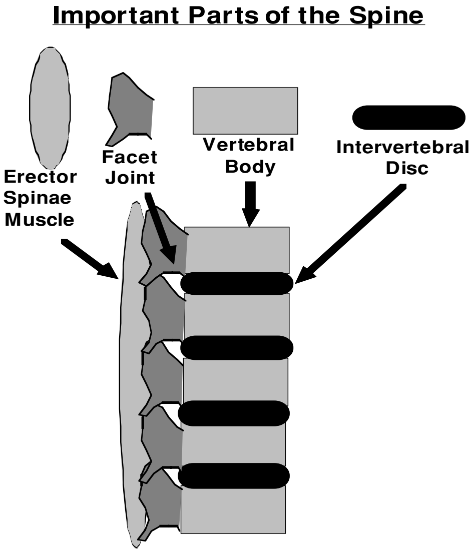


FIGURE 6.4.7 Structure of the spine.

pain include lifting, bending, static work posture, slips and falls, vibration, and trauma [17]. NIOSH [16] lists the following factors as important to low back pain:

1. Lifting of heavy objects
2. Lifting and moving bulky objects
3. Lifting objects from the floor
4. Lifting objects frequently
5. Twisting with loads
6. Poor coupling between the hands and the loads

The six factors suggest four types of risk: (1) the weight or force required to lift the object, (2) the distance the object is located from the body at the beginning and during the lift, (3) the frequency of lifts, and (4) the amount of lateral twisting when moving loads. Additionally, manual material handling jobs that require excessive amounts of strength, regardless of the weight of the object moved, can increase the risk of injury [18]. These risk factors indicate that excessive loads on the back are a primary cause of injury.

In order to perform a quantitative evaluation of the strength demands of a job, it is necessary to determine the following:

1. The percentage of working adults (males and females) who have the strength capability to safely perform the job.
2. The magnitude of the forces acting on the lumbar region of the spine. These forces can manifest themselves in a variety of ways. One measure that is relatively easy to review is compression on the intervertebral discs of the lower spine.

Simple Measures of Spinal Loading. Two concepts must be understood to appreciate the impact of the work environment on the cause and prevention of low back problems in industry. These are *moment* and *compressive force.*

MOMENT: A *moment* is defined as the quantity necessary to cause or resist the rotation of a body. This can be thought of as the effect of a force acting over a distance, or (force × dis-

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tance). *Torque* is a special case of moment and is defined as a moment around a longitudinal axis.

To calculate a moment, recall the concept of a lever arm lifting an object. When balanced, the force on one side of the lever arm must be equal to the force on the other side (see Fig. 6.4.8). In order to calculate this force, one must know the weight of the object being lifted and the distance the object is away from the fulcrum point. The equation for moment is:

Moment = (weight of object) × (distance from center of weight of object to fulcrum)

In order to make the moment concept more applicable to lifting in the workplace, the contribution of the upper body to the moment calculation must be incorporated into the basic equations. This requires some knowledge of the distance between the segment mass center, that is, the center of mass of the trunk, neck, and head unit, and the pivot points, that is, the L5/S1 region of the spine near the hip. If we assume the length from the hip to the center of mass for the trunk, neck, and head unit is approximately 25 cm (10 in), then the moments for any lifting posture can be *estimated.*

As an example, let's assume that an 890-newton person is bending over 60 degrees from vertical with the same weight and the load is held 0.51 meters in front of the body. The moment calculation is as follows (see Fig. 6.4.9):

First, the distance between the spine and the center of mass of the trunk, neck, head, and arm unit must be determined. This can be done by knowing the cosine of the angle is equal to the length of the adjacent side of a right triangle divided by the hypotenuse. The hypotenuse is estimated to be 0.25 meters (length between the hip and the center of mass of the trunk, neck, head, arm unit), and the angle is 60 degrees. Also, approximately half the total body weight is above the hips. Therefore:

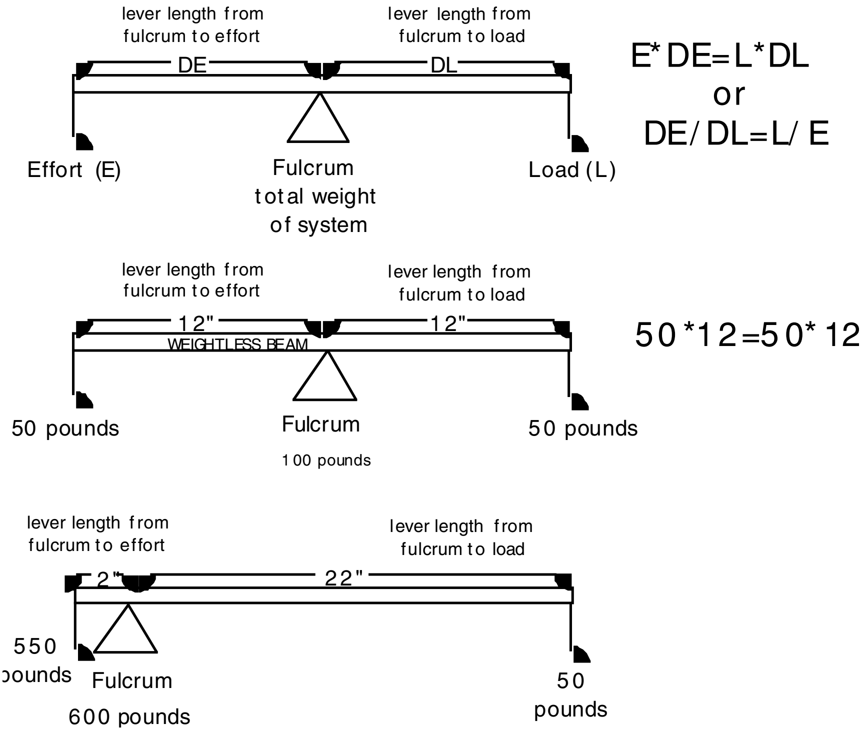
lever length from fulcrum to effort
lever length from fulcrum to load
DE
DL
E* DE=L*DL
or
DE/DL=L/E
Effort (E)
Fulcrum
total weight of system
Load (L)
lever length from fulcrum to effort
lever length from fulcrum to load
12"
12"
WEIGHTLESS BEAM
50*12=50*12
50 pounds
Fulcrum
100 pounds
50 pounds
lever length from fulcrum to effort
lever length from fulcrum to load
2"
22"
550 pounds
Fulcrum
600 pounds
50 pounds

FIGURE 6.4.8 Lever arm model.

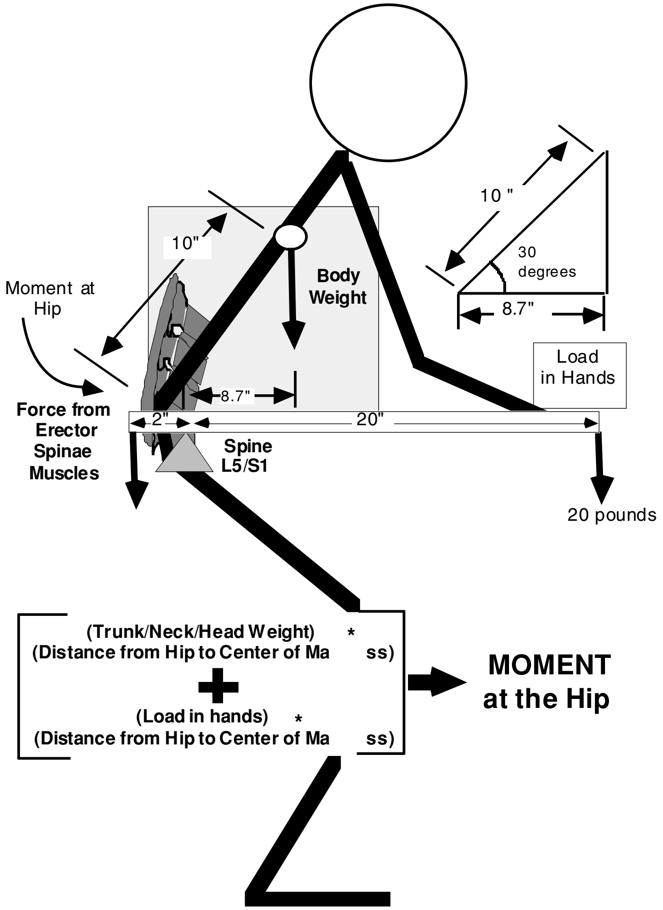
10"
10 "
30 degrees
8.7"
Moment at Hip
Body Weight
Load in Hands
8.7"
2"
20"
Force from Erector Spinae Muscles
Spine L5/S1
20 pounds
(Trunk/Neck/Head Weight) * (Distance from Hip to Center of Mass)
+
(Load in hands) * (Distance from Hip to Center of Mass)
MOMENT at the Hip

FIGURE 6.4.9 Moment arm calculation for upper body.

$$\text{Cosine } 30° = 0.87$$

$$\text{Length of hip to center of mass of trunk/neck/head/arm} = 0.25 \text{ meters}$$

$$\text{Length of the adjacent arm (distance between the center of mass and the spine)}$$
$$= 0.25 \text{ meters} \times 0.87 = 0.22 \text{ meters}$$

$$\text{Moment} = (\text{Weight of Object}) \times (\text{Distance from Center of Weight of Object to Fulcrum})$$

$$\text{Moment from the weight } (M_w) = 89.6 \text{ newtons} \times 0.51 \text{ meters}$$

$$M_w = 45.7 \text{ newton-meters}$$

$$\text{Moment from the upper body } (M_{up}) = 445 \text{ newtons} \times 0.22 \text{ meters}$$

$$M_{up} = 97.9 \text{ newton-meters}$$

$$\text{Total Moment at the hip for lifting 89 pounds under these conditions } (M_t) = 45.7 + 97.9$$
$$= 143.6 \text{ newton-meters}$$

Bending the back 60 degrees from vertical and holding the weight 0.51 meters in front of the body produces a moment that is slightly less than four times that of an erect posture and holding the weight 0.254 meters from the body.

COMPRESSIVE FORCE: It is important to note what the implications of moment are to understanding stress to the human body. Using simple moment calculations may be helpful in characterizing the stress to the human body and may lead to indices of biomechanical stress to specific joints on the body. It is known that when muscles are put under repeated excessive loads, they will experience mechanical strain to their structural systems (e.g., tendons, ligaments, muscles). Data exists that displays the amount of strength available to the body at each skeletal joint. This data is based on tests from United States working populations. Through the use of statistical analysis and analysis of moments, equations were developed that can predict the amount of strength required for a given body joint in a given posture. Once predicted, the analysis can be compared to the population data to determine the percentage of the populations with the available strength to perform the task [19].

Simple low back compressive force prediction models, which predict (if some simplifying assumptions are made) the back compressive force through the use of load weight, body weight, torso angle, and the distance that the load is held out from the body, are available. Figure 6.4.10 illustrates the model input.

Task redesign priorities may be established by comparing the relative values of terms A, B, or C (see Fig. 6.4.11). Note that: (1) term A is the back muscle force reacting to upper body weight (to lower this, change the upper body angle with the horizontal); (2) term B is the back muscle force reacting to load moment (to lower this, change the magnitude of the load or the distance that the load is held out from the body); and (3) term C is the direct compressive component of upper body weight and load (to lower this, change the magnitude of the load or body weight). Term C is seldom, if ever, the largest term and when it is the largest, the back compressive force will be low.

This simplified model tends to underpredict low back compressive force for two lifting conditions: (1) with low weights (5 to 10 lb) when the worker is standing straight up with the

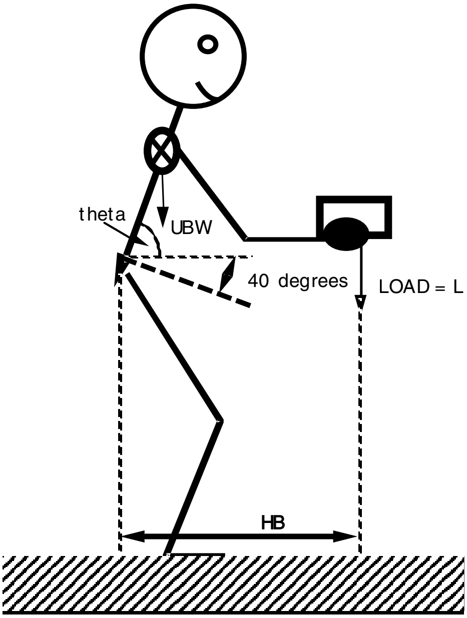

FIGURE 6.4.10 The University of Utah simple biomechanical model of lumbar spine.

arms extended far in front of the body, and (2) with all weights (highest percentage underprediction with low weights) when the worker is in an extreme squat position with the knees bent. This model has several limitations: (1) it approximates the compressive force through simple moment calculations and does not recognize the possible assistive moment caused by intra-abdominal pressure; (2) it assumes the relative distribution of body weight is the same for males and females; and (3) it assumes the orientation of the disc at the low back remains constant at 40 degrees below the horizontal.

Figure 6.4.11 is a worksheet that can be used to calculate the compressive forces using this simple model (English units only). More sophisticated models are available that can predict compressive force to the lower spinal disks. Some of these models include three-dimensional measures, dynamic measures, and so forth. If the issue being analyzed requires this level of analysis, then a more developed model should be used.

Shoulder Moment. Stresses at the shoulder are also frequently of concern in manual material handling tasks. The shoulder moment resulting from a particular load (and resulting shoulder stress) can be estimated if some simplifying assumptions are made. The moment at the shoulder depends on the weight of the load, body weight (arm weight), and the distance that these two weights are located in front of the point of rotation (shoulder). Figure 6.4.12 is a worksheet that can be used to calculate shoulder moment using this simple model (English units only). Substitute BW, D, L, into the equation to estimate the total moment required at the shoulder ($\mathrm{M}_{\mathrm{task}}$ expressed as in-lb). The tables in Fig. 6.4.13 indicate the maximum strength of an average male/female in that posture (upper arm angle, lower arm angle). Record the value from the tables based on angles A and B (M_{cap}). The ratio of $M_{\mathrm{task}}/M_{\mathrm{cap}}$ represents the required shoulder moment as percent of the maximum for the average male/female.

BW = BODY WEIGHT lbs.
L = LOAD IN HANDS ______lbs.
HB = HORIZONTAL DISTANCE FROM HANDS TO LOW BACK ______in.
THETA = TORSO ANGLE WITH HORIZONTAL______degrees
where: If torso is vertical, use cosine (theta) = 0.00
If torso is bent ¼ of the way, use cosine (theta) = 0.38
If torso is bent ½ of the way, use cosine (theta) = 0.71
If torso is bent ¾ of the way, use cosine (theta) = 0.92
If torso is horizontal, use cosine (theta) = 1.00
then: Fc = A + B + C
Where: A = 3(BW)cos(theta) = 3(______)*(______) = ______
B = .5(L * HB) = .5(______)*(______) = ______
C = .8[(BW)/2 + L] = .8[(______)/2 + ______) = ______
Total Compressive Forces ______lbs.
(note: pounds × 4.448 = newtons)

Remember that:
3(BW)cos(theta) = back muscle force reacting to upper body weight. To reduce this contribution, one must reduce the upper body angle with horizontal.
.5(L * HB) = back muscle force reacting to the load. To reduce this contribution, one must reduce the magnitude of the load and/or the distance the load is held from the body.
.8[(BW)/2 + L] = direct compressive component of upper body weight and the weight of the load. To lower this contribution, one must change the load magnitude.

FIGURE 6.4.11 Simple low back compressive force prediction model worksheet.

Shoulder moment worksheet

BW = BODY WEIGHT (lbs) ______
D = HORIZONTAL DISTANCE FROM LOAD TO SHOULDER JOINT (in) ______
L = LOAD WEIGHT (lbs) ______
A = Forearm angle in degrees ______
B = Upper arm angle in degrees ______

$\mathbf{M_t = M_b + M_f}$

Where: $M_b = 0.0115 \times D \times BW = 0.0115 \times$ ______ $\times$ ______ $=$ ______
$M_f = 0.5 \times D \times L = 0.5 \times$ ______ $\times$ ______ $=$ ______
$M_t = M_b + M_f =$ (in lbs) ______

Note that:

M_b = Moment at the shoulder due to the weight of the arm;
M_f = Moment at the shoulder due to the weight of the load in the hands;
M_t = Total moment at the shoulder = M_{task}

FIGURE 6.4.12 Shoulder moment worksheet.

$M_{task} =$ ______ (from Fig. 6.4.12)

$M_{cap} =$ ______ (from table based on angles A, B)

$M_{task}/M_{cap} =$ ______ × 100.0 = percent maximum

There are no generally accepted limits with which the estimated shoulder moment may be compared. Two of the variables that determine the shoulder moment that individuals may be able to generate on a task are *gender* and *arm posture*. Tables have been developed which provide an estimate of the maximum shoulder moment capability for an average male and female as a function of the included angle of the forearm and upper arm. These tables and a figure indicating these angles are included on Fig. 6.4.13.

The metric proposed as a measure of the stress at the shoulder is the ratio of the shoulder moment required by the task, as calculated by the worksheet (M_{task}), and the maximum strength of an average male/female in that posture (M_{cap}). While there are no empirically determined acceptable limits for this ratio, it is proposed that ratios below 0.5 (task-required shoulder moment is less than half of the maximum for the average male/female) will not present a hazard for most workers unless the frequency is quite high, while ratios above 1.0 (task-required shoulder moment exceeds the maximum for the average male/female) will present a hazard for many members of the workforce. The relative contribution of the arm weight to the moment (M_b) and load weight to the moment (M_f) do not provide much meaningful information.

As was the case with the estimate of compressive force, if precise shoulder moment data is required, one of the more sophisticated computer models should be used!

Methods to Measure Multiple Risk Factors in Manual Handling Tasks. Jobs that require manual lifting and handling of objects have been associated with increased rates of low back pain and other related musculoskeletal disorders [14]. Because of the hazards associated with lifting, the National Institute for Occupational Safety and Health issued a technical report entitled *Work Practices Guide for Manual Lifting* [4]. This document discusses the various risk factors correlated with lifting and also describes procedures for evaluating and classifying lifting tasks. It was updated in 1991 to accommodate asymmetrical lifting and coupling [16].

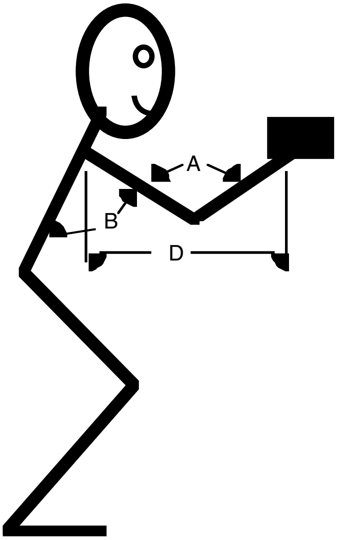

FIGURE 6.4.13 Maximum shoulder moment capability (M_{cap}) of average females and males for different postures.

Other methods are available that utilize multiple factors to analyze a variety of material handling situations. However, when using any of the previously described methods, care must be taken to input the proper data and to observe the model's limitations in work situations.

Activities Involving Assembly and/or Disassembly Activities

When designing or redesigning jobs to control *cumulative trauma disorders* (CTDs), one must measure the risk factors associated with the design for two reasons: First, it is important to analyze the jobs to identify the problems that need intervention to correct. Second, once corrections have been made, it is important to determine the effectiveness of the redesign in reducing the degree of risk.

Since very little research has been completed showing which risk factors or interaction of factors contributes most to the development of disease, the most reliable way to measure the risk of injury is to measure all the risk factors. A summary of the major risk factors and corresponding measurement systems for the upper extremity follows.

Risk Factors. Although there are a large number of cumulative trauma disorders, many are caused by the same or similar work activities. In general, the occupational factors that can increase the risk of CTDs include: repetitiveness, forcefulness, awkward postures, vibration, mechanical stress concentrations, and cold temperatures.

Of these factors, the first three are probably the most important. The more risk factors that are present in a single job, the greater the potential for injury. Although it may not always be possible to eliminate all of the risk factors from the job, the more that can be eliminated or reduced, the better. The impact of each of these factors is as follows:

Repetitiveness. The traditional way to measure repetitiveness is simply to count the number of cycles occurring during a shift. On the basis of this definition, jobs with short cycle times are more repetitive than jobs with longer cycle times because they require the operator to repeat the operation more often. A study conducted by Armstrong et al. [20] considered cycle times shorter than 30 seconds (jobs with 1000 or more cycles per shift) as being highly repetitive.

Jobs with cycle times greater than 30 seconds often require the operator to make many similar repeated motions within the cycle. In such cases, measuring the number of cycles per shift may not be an adequate method of measuring job repetitiveness. Consequently, the concept of *fundamental cycles* was developed. Fundamental cycles are defined as a repeated set of motions or elements within a cycle. Jobs with a high percentage of the cycle time (50 percent or more) spent performing the same fundamental cycles are considered as repetitive as jobs with a cycle time of less than 30 seconds [20].

Cycles and fundamental cycles together constitute one classification system for repetitiveness. But this system considers only the speed at which the operator is performing the job, not the actual movements. Repetitiveness could also be measured in terms of the number of movements or posture changes per shift. Several studies have associated movements with the prevalence of CTDs. Hammer [21] found that jobs requiring greater than 2000 hand manipulations per hour were associated with the development of tendonitis. Repeated wrist flexion and extension have been correlated with carpal tunnel syndrome [22–25].

Forcefulness. Forcefulness is the amount of effort required to maintain control of materials or tools. A number of factors will affect the amount of force that an individual can exert:

- *Type of Grip:* The two basic types of hand grips are the *power grip,* or *full hand grip,* and the *pinch* or *fingertip grip,* as shown in Fig. 6.4.14. The strength of a power grip is four or more times greater than a pinch grip.
- *Type of Activity:* Types of effort activity include *lifting, lowering, pushing, pulling, carrying,* and *holding.* The forces that can be maintained for these activities are highly dependent on body posture, type of grip, duration, and repetitiveness of the activity.
- *Posture:* Effects of posture on forcefulness include the location of the hands with respect to the body when a force must be exerted, whether one or both hands are used, and the direction in which the force is applied.

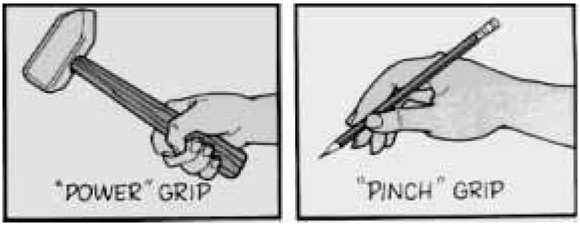

FIGURE 6.4.14 Power versus pinch grip.

- *Duration and Repetitiveness:* The longer the duration or length of time that the force must be exerted, along with the more repetitions required, the lower the exertion force that can be maintained without injury and fatigue.

Force can be measured in a variety of ways—most simply by weighing objects. But depending on the size of the object, the grip type, grip surface, and other factors, the force requirements may change. Consequently, this method does not give any indication of the actual force required to hold the object in the hand. Therefore, a system that directly measures actual hand force is necessary.

One such system incorporates the use of *electromyography* to measure muscle activity in the finger flexor muscles of the forearm. Electromyography (EMG) essentially measures the motor unit potential of twitching muscle fibers [1]. As muscle tension increases, EMG activity increases concurrently [26–28]. Because of this relationship, it is possible to make a reasonable estimate of muscle force (in this case grip force) by measuring EMG activity.

Awkward Postures. The ideal working posture shown has the elbows at the sides of the torso, the wrists straight, and a power grip (see Fig. 6.4.15). Working postures that involve reaching up, out, or behind the body and bending or twisting of the wrists will increase the potential for CTDs.

The measurement of the number of movements or posture changes during a shift requires the accurate recording of postures during a job cycle. A system for posture targeting developed by Armstrong [29] and based on the work of Corlett et al. [30] divides the upper extremity into its individual joints and defines their position in space with reference to the body. The positions of the joints are analyzed for each degree of freedom of movement, including three degrees of freedom for the shoulder and two for the elbow and wrist. Because it is impossible to analyze the angles of each joint to the nearest degree, zones or ranges of angles are used to estimate the position within a specific range. This analysis allows the categorization of postures into zones of stressfulness.

The problem with this system rests with the researchers' transcription of the videotaped data to the record forms. This process, with its dependence on detailed extracting of all postural information, requires a considerable amount of time for completeness and accuracy. This problem can be addressed by automatically recording the postures of specific joints by electrogoniometry. Not only will this approach improve the accuracy of the data collection, as will subsequently be discussed, but it will automate data acquisition from the videotape to the record forms.

Vibration. The prolonged use of many types of vibrating tools, especially in combination with awkward postures and cold environments, can adversely affect worker health, potentially causing damage to nerves, blood vessels, and bones.

Mechanical Stress Concentrations. Stress concentrations over the soft tissue structures of the hand can result from poorly designed hand tools that dig into the base of the palm or fingers, the handling of sharp objects, or using the hand as a hammer. These activities compress the nerves and

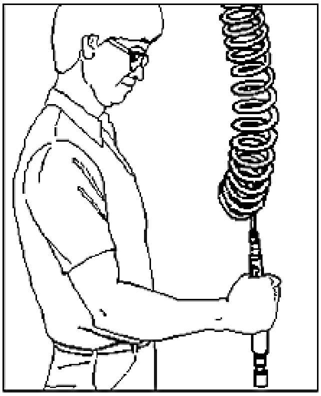

FIGURE 6.4.15 Optimum working posture.

blood vessels in the hand, contributing to a number of CTDs. Likewise, mechanical stress concentrations can also occur at the elbow if it is resting on or rubbing against a hard surface for long periods of time.

Cold Temperatures. Cold temperatures can decrease the sensory feedback to the hands. This in turn increases the force or strength requirements of the job. This can also increase the risk of operators dropping or losing control of tools or materials, creating a potential hazard for the individual or other workers in the area.

Controlling Risk Factors for Assembly-Intensive Activities. The causes of repetitive motion disorders are very complex and no single job factor can be identified. Likewise, whether the job activity aggravates a previously existing illness or contributes to its development is also not clear since not everyone performing a given job will develop symptoms. Since it is not always possible to predict which individuals will develop symptoms, it is necessary to identify and eliminate those workplace factors which have been associated with the risk of developing repetitive motion disorders for the benefit of all individuals. The following are guidelines that can be used to reduce repetitiveness and its associated disorders.

1. *Reduce repetitive effort.* Use mechanical assists or gravity to transfer parts rather than using the hands; use power assists, tools, or fixtures when forces are high, to eliminate repetitive gripping actions; design tasks so that stressful tasks can be alternated between the right and left hands.
2. *Work enlargement or altered work methods.* Add different elements or steps to the job that do not require the same motions as the current work cycle; for jobs requiring only one hand, organize the work station to allow alternate use of hands; use foot pedals to activate machinery or hold fixtures, to reduce the loads on the hands.
3. *Job rotation.* Allow frequent rotation between jobs that use different postures and muscles until the jobs can be redesigned to eliminate repetitive elements.
4. *Adjust work pace.* Allow new employees, recently transferred employees, or those returning from extended leave to start at a lower rate, so as to enable them to become accustomed to the activity.
5. *Decrease tendon force.* Decrease hand forces; use a power grip instead of a pinch grip; increase mechanical advantage.
6. *Decrease postural hazards.* Redesign tools to reduce wrist deviation; employ use of fixtures to reorient parts; redesign workstation to change relationship of worker and part during job tasks.
7. *Decrease potential for contact trauma.* Use padding on tools and/or workbenches to spread/evenly distribute contact forces; use alternate hands in tasks; redesign workplace.

MANUFACTURING ERGONOMICS—COST AND BENEFIT

Currently, in most manufacturing facilities, all business projects must go through normal purchasing channels to be approved for funding. Unless costs are nominal, these projects must be reviewed for cost/benefits. Funding is awarded based on traditional cost/benefit analysis calculations and expected savings due to either work standards, work practices, or quality.

It may be difficult to use traditional cost systems to justify an ergonomics project. This is because ergonomics projects often do not show significant savings, in the traditional sense, immediately after installation. Instead, the type of savings often seen in ergonomic projects are reductions in health care costs. And these can be difficult to justify if the relationship between injuries and the responsible jobs is not well established.

This lack of an obvious link between an injury and a job yields two results: First, medical costs associated with worker accidents and chronic musculoskeletal disorders are usually not charged directly to the production department responsible for causing the injury. Instead, they are charged to a separate central account in the plant's Industrial Relations Department (or equivalent), thereby partitioning the true costs over the entire plant. This makes it difficult to justify a job change because the benefits are hidden. Second, projects often have to be justified on the basis of traditional cost/benefit analysis and computed in terms of plantwide and area productivity (e.g., completed pieces per hour).

The following is a list of some of the costs involved in installing new equipment. All these costs should be considered in order to accurately determine the costs of implementing ergonomics projects and changes on the plant floor. It is recommended that a form be developed that records these costs for later analysis.

1. *Design time.* The time and resources involved in designing projects.
2. *Engineering time.* The time and resources involved in engineering the project.
3. *Tool change.* The fabrication costs and time necessary to fabricate a set of tools for the project.
4. *Skilled trades time.* Manpower needs for installing, testing, and maintaining the project.
5. *Materials.* Cost of materials for the new project.
6. *Machine downtime.* If the project is going to directly affect an existing line, that line may have to schedule downtime to properly install the project. Therefore, downtime and lost production must be budgeted into the installation costs.
7. *Training.* When new equipment and/or processes are implemented on the plant floor, operators responsible for running and maintaining the equipment must receive training.

In summary, Fig. 6.4.16 depicts the relationship between the cost and benefits of ergonomics. Because of the problems of using traditional cost/benefit analysis, it becomes more important to document all of the costs associated with poor job design and all the benefits after ergonomic intervention. Therefore, it is often best to make simple, inexpensive changes first. As poorly designed jobs are identified, the data (as previously outlined) should be collected and analyzed before and after the proposed job changes. As more data is collected and the cost/benefit equation becomes better defined, it should be easier to justify job changes.

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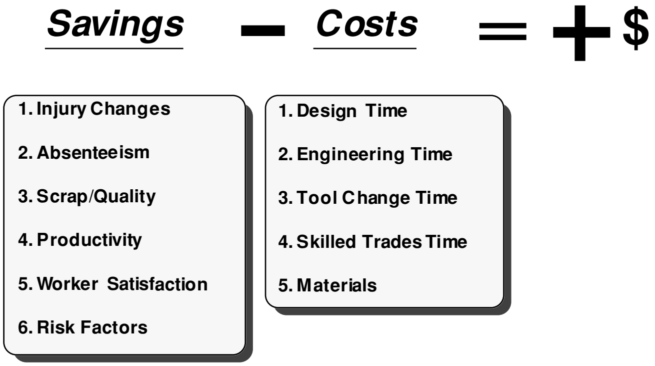

FIGURE 6.4.16 Cost/benefit summary.

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CHAPTER 6.5

ERGONOMICS IN THE OFFICE ENVIRONMENT

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Ergonomics in the office environment ranges from business process analysis to workplace design regarding furniture, equipment, computer systems, and environmental factors. This chapter will focus on ergonomic aspects of nonterritorial offices and its consequences in the change of work practices, office designs, and tools. The chapter will keep a practical approach to the subject, and the content is based on research work as well as hands-on experience. The objectives are to give the reader a broad overview of the different aspects of ergonomic issues applicable to office work. The chapter focuses on the requirements found in offices planned for flexible work practices (i.e. nonterritorial offices). However, most requirements are applicable to any office environment.

THE OFFICE AS A TOOL FOR OFFICE WORK—A BUSINESS PROCESS ANALYSIS APPROACH TO OFFICE DESIGN

Introduction

The established view of office design and office work has been contested by many companies since the beginning of the 1990s. Questions such as, "Why do we have offices?" and "Why do we work the way we do in offices?" have led to the emergence of a number of alternative solutions to office design. Most of them are based on the concept of *nonterritorial* or *free address* offices in which a given desk, office, or workstation is intended to be used by different people at different times.

It must, however, be understood that the physical design of the office is only a part of the change. Alternative working styles and changes in organizations have had an even greater impact on the behavior of the people working in the office. It is important that the management has a clear understanding that when transforming the office to support flexible work practices the primary focus must be on people's needs and behavior rather than on actual interior design [9].

Based on experiences from research performed in the United States [1] and Sweden [2, 7], some critical factors for success of the office design process have been identified. These include:

- A clear identification of the project owner
- Projects that are productivity driven and not cost driven
- Identification and realization of benefits for the office staff—"What is in it for me?"
- Staff involvement in the process
- All aspects of the project considered as a whole, including the available space, interior design, information technology, organization, and working practices
- Good interior design
- Openness and flexibility to meet future requirements

Hands-on Experience

Research projects, with the objective of evaluating the working environment of the "flexible office" concept, have been carried out in Sweden [3]. A summary of the outcome of one of those projects follows:

The purpose of the project was to evaluate five new offices based on the "flexible office" approach and to compare the results of the evaluation with the implementation process. The five offices are branch offices in the same company, but due to a regional organizational setup the implementation process was carried out in very different ways in different offices. The conclusion points out the importance of the process and how it is managed. Figures 6.5.1 and 6.5.2 illustrate and describe the results from two of the offices in comparison with the total population.

The black rectangles in the figures represent the mean value for the particular office and the gray and white bars describe the levels of confidence for all five offices (the same in both diagrams). Rectangles positioned on the left or the right side of the median line (50) therefore represent the level of dissatisfaction or success for that office. Thus Fig. 6.5.1 shows an office where the personnel are quite satisfied with their new office design and work practices, while Fig. 6.5.2 shows an office with the opposite result.

Evaluation projects like the one just described put the focus on the implementation process.

Flexible Office and Work Practices

One of the most important factors when carrying out a flexible office design or redesign project is the awareness that it is a project of changes that primarily affects staff and organization, and only secondarily a building project. *You cannot redecorate your way to flexible work practices!* This also means that you cannot easily transfer an existing office design from one organization to another. Instead, every office must be created by and for its own staff and organization. The business process analysis is therefore a fundamental element in the design of the flexible office.

This emphasizes the need for a master plan—an *office design process* (ODP). This process could be described in several steps. Milestones in a proposed office design process [4] are presented in Table 6.5.1.

The steps listed in Table 6.5.1 contain a number of different subactivities that should be carried out for a successful project implementation.

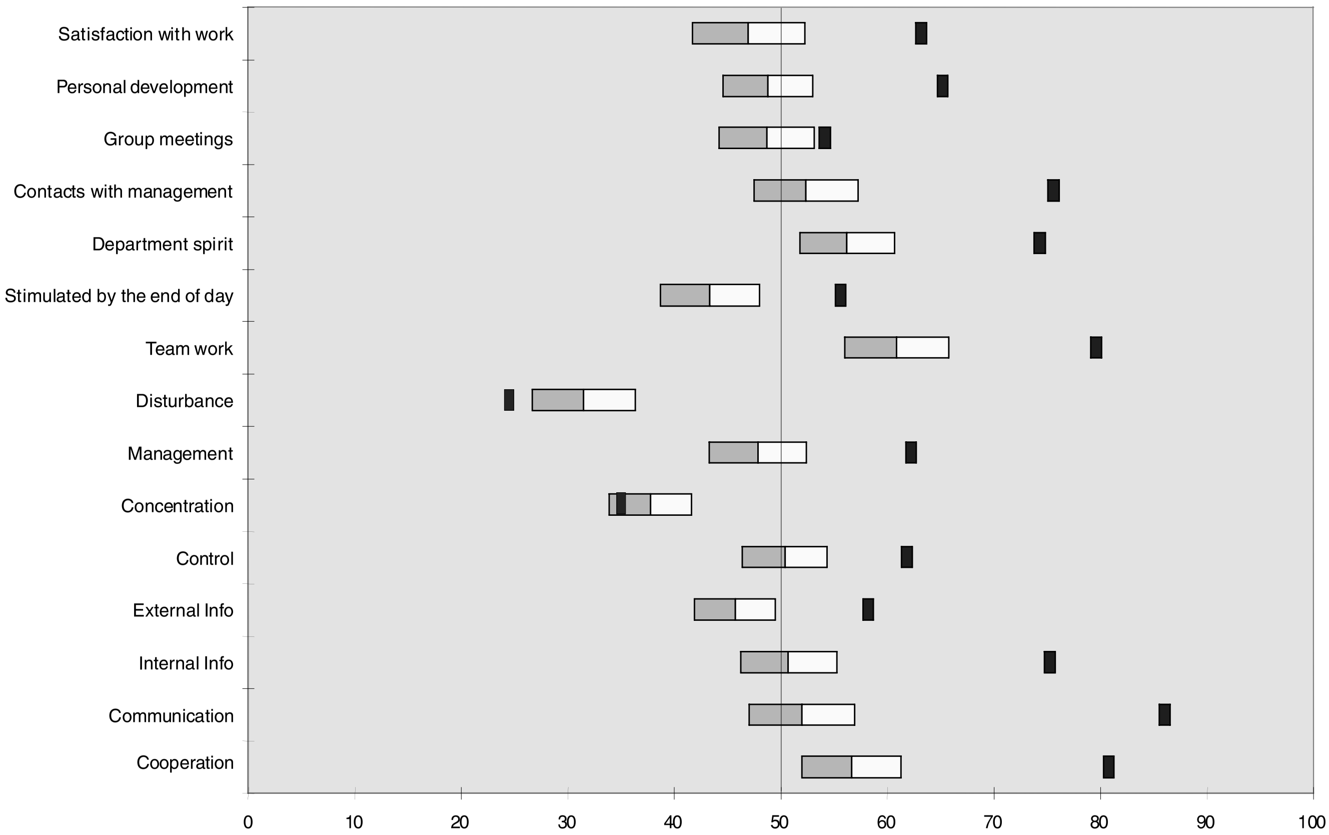

FIGURE 6.5.1 Results of survey regarding employees' opinions of their new office design and work procedures.

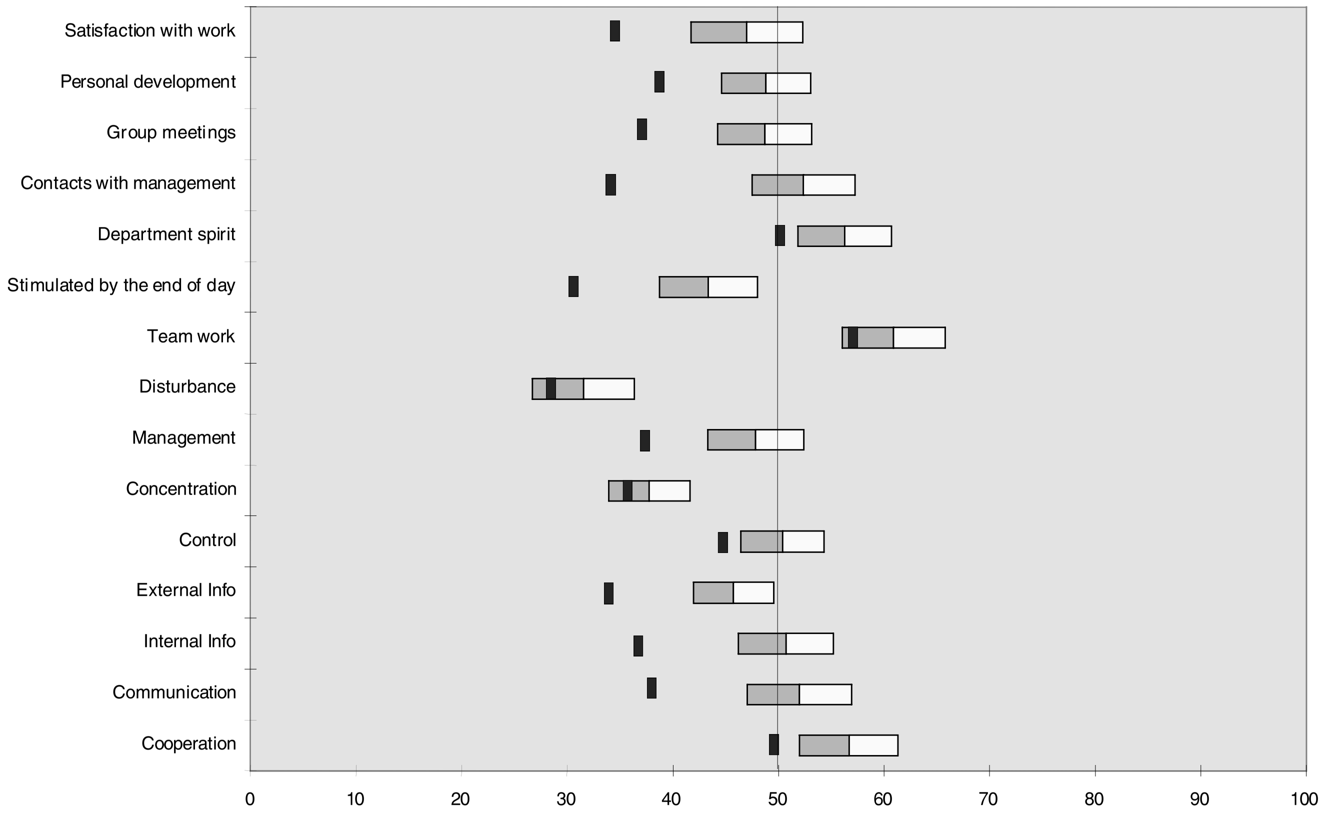

FIGURE 6.5.2 Results of survey regarding employees' opinions of their new office design and work procedures.

TABLE 6.5.1

- Establish the main objectives for the project
- Presentation to staff to explain what is going to happen
- Feasibility study
- Presentation of the results
- Checkpoint/decision time
- Presentation of project status
- Base line study
- Set objectives on all levels
- Presentation of ongoing activities
- Project planning
- Project presentation
- Create a staff working group
- Business process analysis
- Architectural design proposal
- Training
- Choice of accessories
- Choice of IT and telecom equipment
- Construction planning
- Team training
- Presentation of activities outside the organization
- Moving into the new office
- Orientation and support in the new office
- Follow-up and evaluation

Does a Flexible Office Support Good Ergonomics?

In an ergonomic research project [2], staff members working in flexible and traditional office designs were asked to report the sensation of body strain. The results are presented in Fig. 6.5.3. The filled (black) bars show the result from the traditional office and the unfilled (white) bars represent the flexible office. The "standard" report for Swedish people working in an office environment concerning the presence of body strain in neck and shoulders is between 30 and 35 percent. In this case, the reported level in the traditional office design meets the expected value. The reported value from the flexible office design is much lower. There are no reports concerning strain in elbow, forearms, wrists, hands, or fingers from the personnel working in the flexible office design. One explanation is the increased flexibility in working positions that the furniture and work organization offer in this type of office.

OFFICE USABILITY—ERGONOMIC ASPECTS OF THE ORGANIZATION OF OFFICE WORK

Introduction

To succeed with an office design concept based on flexibility and openness requires a new and different way of looking at offices. The office must be regarded more as a tool, like any computer or telephone system, with the main purpose of supporting the business tasks. The organization of computer-based tasks has proven to have an essential impact on the comfort of the user.

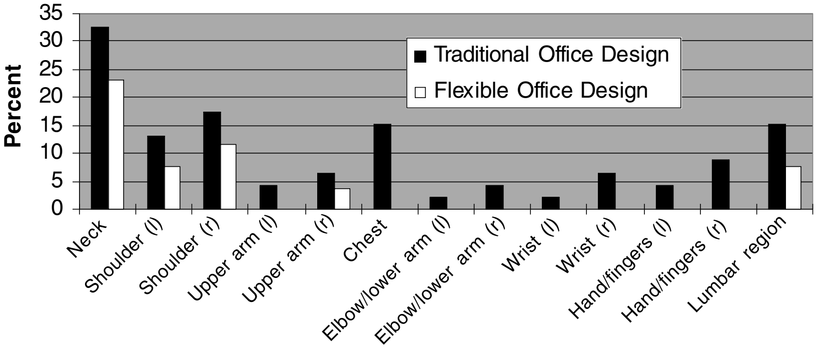

FIGURE 6.5.3 Reports on body strain.

New Ways of Working

A flexible office design offers more than just a nice interior. The changes in work organization/work behavior made possible by portable phones, client server computing, open plan office design, group work, and telecommuting have made higher efficiency and better quality in office work possible [8]. Companies that have adopted this working style can present figures and facts that clearly demonstrate the advantages [5]. These include:

- More satisfied employees
- Decrease in sick leave time
- Decrease in staff turnover
- Up to 47 percent increase in working time availability
- Increase of net income (33 percent)
- Less costs for office space (50 percent)

Organizational Changes

Which are the significant organizational changes that result in such numbers? Five activities mainly stand out:

- A strong management-encouraged staff involvement in the change process
- A clear setting of objectives
- A business idea in line with the change process
- A change in management style from control to support and coaching
- Taking advantage of the organizational force that comes with enthusiastic people

There are some prerequisites for this transformation, with modern information technology playing a vital part. Central storage of all common information, digital communication between staff members, and strict routines for computer usage and ways of cooperation are factors that must be considered.

ERGONOMICS IN THE OFFICE ENVIRONMENT

SYSTEM USABILITY—HUMAN-ORIENTED SOFTWARE AND SYSTEMS IN INFORMATION TECHNOLOGY AND TELECOMMUNICATION

Introduction

Usability dictates the efficiency and productivity of a product, as well as the degree of comfort and satisfaction users have with it. Products with poor usability can be difficult to learn, complex to operate, and underused or misused.

Poor product usability leads to high costs for the organization purchasing it, and to a poor reputation for the company that developed it.

It is important to distinguish between *utility* and *usability.* Utility indicates how useful a certain function is, while usability describes how easy it is to learn, use, and remember. A product that does not fulfill the "utility" requirements will not be used, irrespective of how "usable" it is. It is also important to identify the context of the use of a product—for example, there is obviously a difference between how one would use a movie theater chair and an office chair. Good usability is really something you do not notice. It is just there. Poor usability, on the other hand, creates irritation and can cause you to stop using something that might actually otherwise be quite valuable or useful.

How Do You Obtain Good Usability?

Usability can be measured by defining measurable goals, such as:

> "Eighty-five percent of the users should, without error, be able to find a document at the first attempt, without any formal training."
>
> "Seventy percent of all users should experience the new function as a clear improvement over the previous one."
>
> "Ninety percent of the users should be able to send a fax in less than 30 seconds."

A large number of different tools and methods are available for testing and evaluating usability and also to ensure good product usability testing and evaluation of different design proposals, which should be obtained systematically during the entire development process.

Evaluating Usability

There are many different methods and tools for evaluating the usability of computer products [6]. Different methods identify different problems and produce different results and conclusions. Some methods are better suited for the analysis of existing products, some are more suitable for use during early stages of development, and others are most useful toward the end of the development cycle. Some are carried out exclusively by human-factors specialists, and others with the help of representative users.

Several commonly used methods follow. These methods are scientifically based and well established. They can be modified and adjusted to the needs in a certain situation.

Method 1: Feasibility Study. A feasibility study is useful in projects where there is no clear picture as to how to proceed in order to improve the usefulness and/or usability of a product or system. The purpose of the feasibility study is to identify the main usability problems through an expert evaluation. Any hidden costs caused by the problems are identified, solutions to the problems are discussed, and an action plan for additional work is defined. The results address questions about design, user support, education, user participation in the development process, and the activities of the project in these areas.

Method 2: Usability Analysis Through Subjective Assessment. There are some user questionnaires that are very cost effective, giving a quick indication of *user* opinions concerning the usability of the software. The software to be evaluated can be an existing version of a product, a competitive product, or an advanced prototype.

Method 3: Expert Evaluation / Heuristic Evaluation. In a heuristic evaluation, *experts* analyze and assess the usability of a user interface. A number of human-factors specialists (typically five or six) will evaluate a product/system on the basis of 10 design principles. The word *heuristic* comes from the Greek language and means *to explore* or *to evaluate.* A heuristic evaluation identifies usability problems based on the experience and knowledge of a group of experts. Descriptions of the problems are specific, and possible suggestions for improvements are given. About 75 percent of usability problems are usually identified by this type of evaluation. This method can be used at any time during the development process. Either an existing version of a product, a competitor's product, or some form of prototype can be evaluated.

Method 4: Diagnostic Evaluation—a Simple User Test. This technique provides a detailed specification of the usability problems *the user experiences* when carrying out qualified tasks with the selected product or system. The advantage of this approach is that user-specific problems are identified, based on one or several tasks.

The method is most effective if carried out early in the development process. It is most useful in iterative design work, where models or prototypes are tested several times, and improvements or modifications are introduced after each test. Also, existing products can be evaluated. Based on usability targets or the performance of expert users, it is possible (with only about five representative users) to obtain an understanding of product usability.

Method 5: Validation Test or Analysis of Competitive Products. A validation test permits the measurement of product usability based on predefined usability goals. Usability is defined in terms of user performance as well as subjective data regarding user experiences. This method is applied mainly to existing products and answers the question, "How usable is my product?" Competing products can be compared to answer the question, "Is my product more usable than theirs?" or "Which of these similar products is most usable?" A validation test is user-based and gives primarily quantitative data. The result is statistically supported, as typically 12 to 15 representative end users will test the product.

To measure is to know and to test is to know even better.

OFFICE ENVIRONMENTAL ERGONOMICS—LIGHTING, SOUND LEVEL, CLIMATE, AND OFFICE LAYOUT

Introduction

Environmental factors in the office environment play an important role in ensuring comfort and efficiency in task performance. Reflections in video display terminal (VDT) screens, high indoor temperature, and disturbing noise levels are factors that could occur in cases of bad office planning. The negative impact of those factors must not be overlooked.

Office Lighting

Office lighting should meet a number of requirements to provide high-quality illumination. Low-quality lighting is tiring both physically and mentally. Even though inadequate lighting in most cases does not make vision impossible, the signals from the eyes to the brain can result in interpretation problems.

Unsuitable lighting can lead to difficulty in concentration as well as in poor working performance. In addition it can also cause muscular strain as a result of the worker being forced to sit or stand in awkward positions.

Lighting in offices must ensure sufficiently high levels of illumination in requested areas, such as reading areas and computer operation areas. There must be no distracting reflections within the normal field of view, and specific requirements in respect to luminance levels should be met.

Besides visual conditions, energy efficiency and environmental implications must be considered [10].

Visual conditions to be considered are:

- Illumination
- Placement of accessories in relation to work station
- Glare, luminance, and luminance distribution
- Contrast reduction
- Color rendering and color temperature
- Reflectance factors
- Flickering
- Installation
- Electric and magnetic fields

For energy efficiency, special high-frequency operation lights, installed wattage, and the total use of energy are of interest. Research work in Sweden has shown that an installed wattage level of as low as <10 W/m^2 still can maintain good ergonomic light quality [16].

Special considerations for the workstations in a new office are that the workstations (desks with monitors) can be pointed in different directions within the same area, and that they can also be placed at different heights. This influences the choice of light fixtures.

It can often be difficult to shade ordinary fluorescent lights with lighting turned down to avoid direct glare from occurring at any angle. In this environment it is therefore appropriate to have well-shaded fittings, either turned down with a deep-lying light source or a fitting with 100 percent upturned light. In a good light environment, a combination of these fitting types is recommended. It is also appropriate to use fixtures capable of high-frequency operation, so that light flickers do not arise.

With 100 percent upturned light you should think about choosing a distance between the fitting and the ceiling so that a reflection glare does not arise.

Local lighting should be designed so that a person sitting down at a workstation will not be blinded by the local lighting that a nearby standing person has at his or her workstation.

Sound Level

Because sounds from conversations between colleagues and telephone conversations are the largest cause of disturbances in this type of environment, it is important in both cases to apply a certain amount of telephone discipline. Simultaneously, great efforts are made to create an interior design equipped with the prerequisites for a good sound environment.

The recommended reverberation time for office space is 0.4 to 0.6 seconds, and one method to manage this is to create many surfaces using sound absorbent material [11]. Examples of this are textiles on the walls and the ceiling, perforated slabs as an esthetic element in the office environment, plant arrangements, and so forth. It is especially important to have curtains in front of glass walls, since glass surfaces have low sound absorbency. The sound of steps is another source of disturbance, and one should consider using a floor material with a muffling effect in the passage areas.

Another method that has been tried is to use "white noise," that is, barely detectable music that reduces the worker's comprehension of what others on the premises are discussing.

When textiles, plants, trees, and the like are brought into the premises, a plan must be drawn up for their maintenance. This ensures, for example, that those with dust allergies will not be troubled.

Climate

A positive aspect that has emerged is that large air volumes in these types of premises create the environment for a good indoor climate. A necessity, however, is that all heat-producing devices such as printers and copying machines are placed in their own location, which should be well ventilated so that the heat from these does not have a negative effect on the overall climate. This is also advantageous in noise suppresion, since these devices are often very loud.

Office Layout

The premises that make up the flexible office environment should not be planned so that they become too large when connected. Experience points to a group size of 15 to 18 employees per workstation area of approximately 200 to 250m^2 (2.150 to 2.700 ft^2) as being appropriate [4]. Within an area of this size one can still feel a certain closeness and have a good general overview. It must be emphasized that several factors affect floor space accessibility per workstation or individual. Different businesses have different requirements, and the occurrence of tele-working and other out-of-office activities affects this. An analysis of business processes should be the basis for the planning of floor space utilization, and therefore one generally cannot determine a specific number of square meters (feet) per person.

The design of the workstation is especially vital in a flexible office, where the adjustment of furniture to suit multiple users must be accomplished in a simple way. For instance, adjusting table heights must be extremely easy to accomplish.

WORKSTATION DESIGN—ERGONOMIC REQUIREMENTS ON TABLES, CHAIRS AND OTHER FURNITURE IN THE OFFICE ENVIRONMENT

Introduction

There is no such thing as an "ergonomic working position." Workplaces and work organizations that support flexibility also support good ergonomics. The ability to alter one's position by sitting, standing, walking, and even lying down in a working situation is healthier than sitting continuously with 90 degree angles in knees and hips. Tables that are adjustable to meet the working height of both sitting and standing positions; telephone and computer systems accessible all over the office; and comfortable, lie-down chairs in quiet areas are examples of designs that support good ergonomics.

Instead of referring to measurements regarding width and depth of tables and other office furniture, the basis for furniture requirements in this chapter is the user and the user's task to perform.

Working surface will then be defined as the width a user needs to accomplish a certain task. Figure 6.5.4 shows an example of ergonomic criteria regarding width and depth of the work

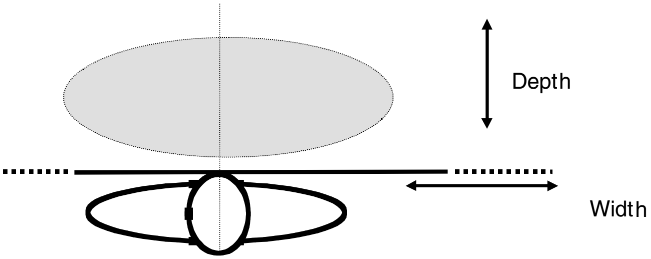

FIGURE 6.5.4 Position—desk illustration.

surface. The width requirement is based on the task—working with a VDT using a keyboard and an input mouse. It is important to have space available for the mouse/input device on both sides of the keyboard.

The depth of the work surface will then be based on the required viewing distance in relation to the screen size. For displays based on the CRT technique there is a relationship between screen size and the depth of the housing. There is also a relationship between character size and the size of the screen. In both cases this means that for a bigger screen a greater depth is required. Figure 6.5.5 illustrates this.

Experience from flexible office environments [3] shows that some types of furniture are more suited than others to encourage and facilitate flexible work practices. Examples of such furniture follow.

Balanced Tables

The balanced table (see Figs. 6.5.6 and 6.5.7) is very appropriate for use as a worktable, since it can easily be adjusted to different heights. To work well, balanced tables must be able to be adjusted, so that they balance the load placed on them.

The desk surface can be designed so that size and shape will specifically accommodate the equipment and tasks to be performed.

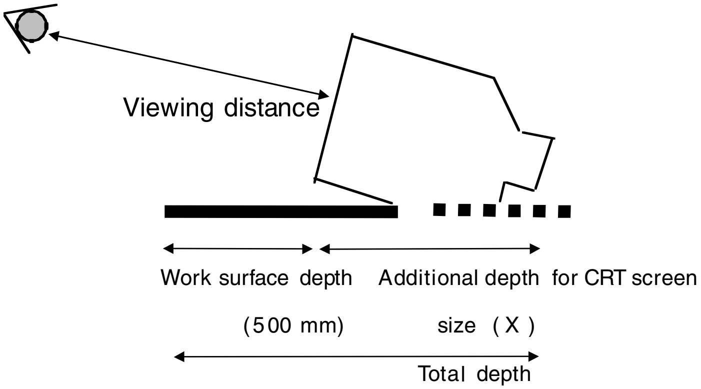

FIGURE 6.5.5 Viewing distance.

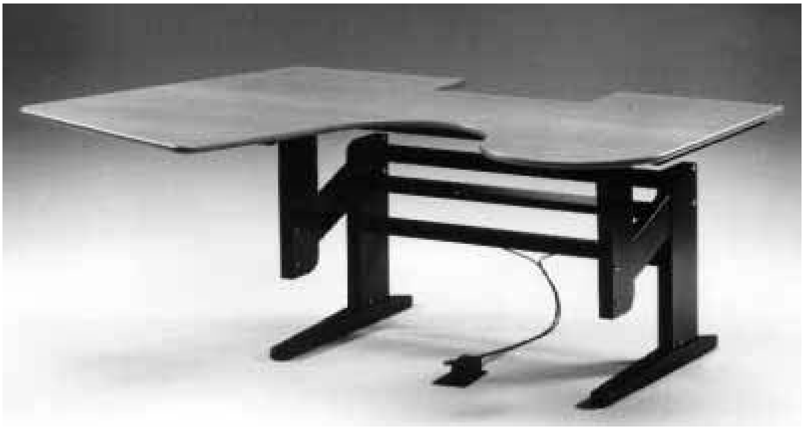

FIGURE 6.5.6 Work desk (low position).

Chairs

To meet the requirements of flexibility, one chair per person is not enough! Even though a certain chair is fully adjustable regarding sitting height, width, and so forth, experience shows that people very seldom change the initial settings. To offer each employee a set of different chairs that support differences in sitting style will contribute to increased health and safety (see Fig. 6.5.8).

Additional Office Furniture

The rolling cabinet (see Fig. 6.5.9) is appropriate to use when the work is characterized by flexibility and when the staff person does not have a fixed workstation. The surface area of the

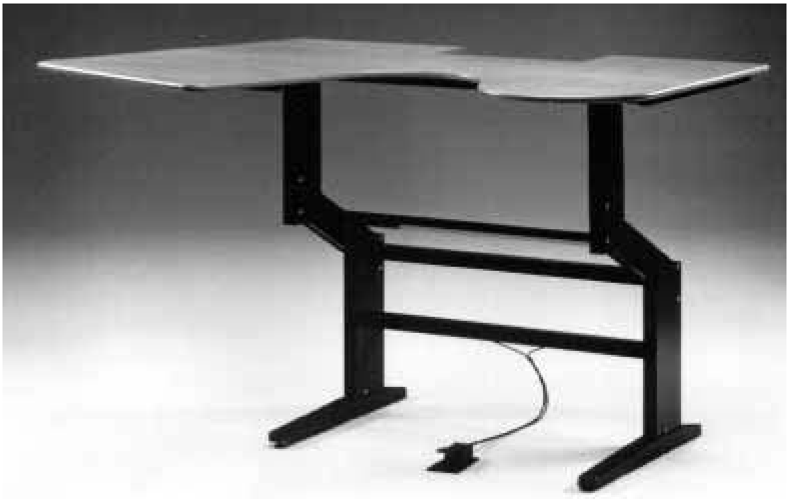

FIGURE 6.5.7 Work desk (high position).

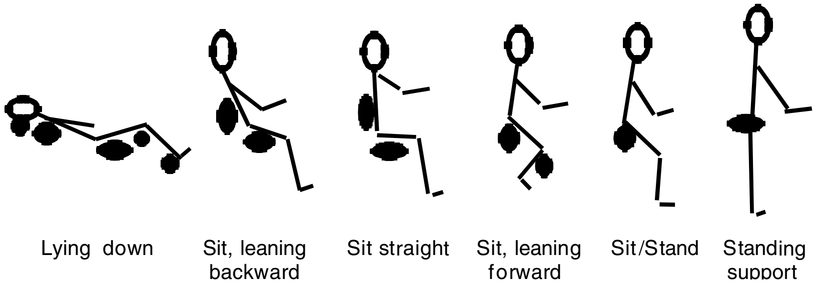

FIGURE 6.5.8 Postures.

rolling cabinet is often used as an extension of existing table surfaces, which means that the "desk" height is controlled by the work height. This is naturally not good from an ergonomic point of view, and therefore the table surface of the cabinet should be introduced as an unloading area.

OFFICE TOOLS—ERGONOMIC REQUIREMENTS ON DISPLAYS, KEYBOARDS AND OTHER INPUT DEVICES

Introduction

Work with visual display terminals (VDTs) in offices is often intense and can occupy a significant part of the individual's working time. The characteristics of displays, keyboards, and other input devices can substantially affect performance and user comfort. Ergonomics has been a strong driving force in the design of VDT hardware, and the results can be seen in low-profile keyboards and displays with black characters on a light background.

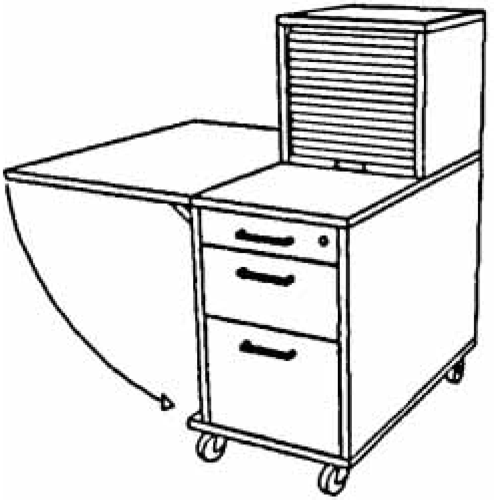

FIGURE 6.5.9 Furniture.

However, even though computer hardware is designed according to the latest ergonomic findings, extensive keyboard input work could still cause muscular problems such as repetitive strain injury (RSI). A flexibility in work practices (including micropauses) and work positions is essential to minimize health and safety risks.

Displays

Factors concerning display ergonomics are related to the physical design of video display terminals (VDTs) as well as user interface design aspects of the software. The software issues have been discussed in the usability section of this chapter.

One of the main factors that affects performance and comfort is the image quality of monochrome as well as multicolor displays. Good image quality is a multifactorial issue, dependent on character design, phosphorus quality (for CRT-based displays), and overall technical quality of the display.

Flat panel technology will enhance the possibilities to arrange work places using proper ergonomics. The easier positioning of the flat display gives more flexibility both regarding the use of the furniture and for the user.

Keyboard

Keyboard layout, key functionality, and design are all essential factors that contribute to user productivity and comfort. Other factors such as thickness of the work surface supporting the keyboard and overall layout of the workstation have implications on the comfort of the users. Low-profile keyboards with a proper tactile feedback are suitable for most users. However, extensive keyboard work, (i.e., several hours per day) is not recommended due to the fact that even limited muscular stress could cause muscular problems if exaggerated.

Mouse and Other Input Devices

The WIMP-concept (Windows, Icon, Menus, Pointing Device) is commonly used today. It is an easier task to choose an object than to remember a certain action command—especially as human/computer communication tends to become more intense and time consuming. Ergonomic aspects of pointing devices (mouse, trackball, joystick, tablets) have been well-studied. The most common input device, the mouse, could, in a bad workplace design, give the user muscular stress problems. This problem has been addressed in a number of technical studies as a substitute to using shortcut commands on the keyboard.

Different input devices present different characteristics regarding speed, accuracy, and preference. The usage is apparently dependent on the application conditions and the task. It is therefore difficult to make general comparisons between different input devices. Another problem to face is that negative output, measured as muscular stress and strain, takes a long time to develop to the point where it can be observed.

The right approach is not to attempt to identify the best input device in general, but to classify input devices based on the task to be performed. Common activities are "choose objects, drag objects, change orientation of objects—rotate and data input." Classification can also be based on "learnability, effectiveness (speed, accuracy), attitude, benefits versus cost (in terms of fatigue, stress, frustration, discomfort), and flexibility."

The usage of input devices can cause muscular stress in the hand / arm / shoulder region. These effects are the combined results of the design of the input device, workstation layout, task, and individual applications. Ergonomic studies [15] have also shown that anthropometric differences related to gender are factors relating to muscular stress. The conclusion is that it is not possible to choose "the right input device" without taking the context of use into consideration [12, 13].

STANDARDS AND GUIDELINES IN THE OFFICE ERGONOMICS DOMAIN

Standardization plays an important role in the field of ergonomics as it is an important channel to bring knowledge of ergonomics and human factors to industry. There is a difference between technical standards that must deal with a dynamic technical development and ergonomic standards that are based on human abilities and limitations, factors that are more constant over time.

Among standards regarding the aspects of ergonomics in an office environment, ISO 9241 and ANSI/HFS 100-1988 could be referenced. A brief description of each follows:

ISO 9241, "Ergonomic Requirements for Office Work with Visual Display Terminals," deals with ergonomics in office work and computer systems. The standard ranges from ergonomic requirements on *Menu Dialogues and Guidance on Usability* to *Workstation Layout and Work* to *Environmental Issues.* ISO 9241 consists of 17 parts, some of which are accepted standards, while others are in a draft (DIS) or final draft (FDIS) status.

ANSI/HFS 100-1988, "American National Standard for Human Factors Engineering of Visual Display Terminal Workstations," covers all aspects of VDT workstations. This standard provides data and specifications to be tailored to each unique work situation, and trained professionals comprise the targeted group. ANSI/HFES 200 is a draft standard in the field of HCI (human/computer interaction) that will cover software usability from a wide range of aspects, including special considerations for people with disabilities.

Besides the standard setting bodies, national and international, several corporations have issued guidelines regarding human/computer interaction and user interface design. Some examples are:

• Apple Computers, Inc.:	*Human Interface Guidelines: The Apple Desktop Interface*
	Macintosh Human Interface Guidelines
• IBM:	*A Guide to Software Usability*
	Common User Access, Advanced Interface Design Reference
• Hewlett-Packard:	*Motif Interface Guidelines*
	Software Usability Design Guidelines
• Microsoft:	*Windows Interface: An Application Design Guide*

Standards and guidelines are useful, but there are limitations. They are helpful in making designers and technicians aware of the ergonomic and human factors aspects of product design and in providing support in solving ergonomic requirements established in the process. However, standards and guidelines are by nature relatively limited and general. This gives a wide range for interpretation, and designers must use their own judgment, based on previous experience, when addressing ergonomic principles in a given design task [14].

FUTURE TRENDS IN OFFICE ERGONOMICS

Flexible offices (i.e., offices where people, employees, and consultants work sporadically) will increase in number in the 2000s. Mobility of the labor market, less rigid terms of employment, and work carried away from the office in different forms will create such demands for changed office design and changed working methods that the traditional office structure of today will no longer be able to compete. From an ergonomic point of view, this puts demands on development of new furnishing systems. The furniture produced in recent years and used in flexible offices today is not sufficiently well developed for future needs, either in terms of function or quality.

Regarding software systems, a more user-centered design approach must be adopted. Usability is critical to the success of computer systems and products. Today, too many systems are difficult to learn, complicated to operate, and often underused or misused. In the future, computer systems must have what is called "quality in use." This includes both cost effectiveness and a design that meet the needs of the intended users of the systems and products.

The development of the flexible office and flexible work will be accentuated during the coming years, and it is therefore of great importance that this line of development is allowed to take place based on ergonomic knowledge and principles.

GLOSSARY

Within the area that has come to be known as the "flexible office," a number of new words and concepts have arisen, while certain older terms have been altered to a certain extent. A number of these are compiled in the following glossary in order to make the reading of the chapter clearer, while also attempting to explain these concepts in an unequivocal manner. The words listed are not arranged in strict alphabetical order. We have instead chosen to place them within the following headings:

- Work practices
- Flexibility
- Physical working environment
- Furniture
- Room concepts
- Spatial concepts
- Miscellaneous

Work Practices

multiflex To work from one's office, home, car, hotel, and so forth. See *Teleworking.*

satellite office A form of teleworking place. A company gains time and work space in a remote "satellite" office which is located closer to an employees' residence than is the company's main office.

teleworking To work outside the office for a given portion of one's working hours. Most commonly, the alternative workplace is found in the home, though teleworking can also be carried out in satellite offices, hotel rooms, customer offices, cars, and so forth.

Flexibility

flexibility Flexibility in the context of flexible offices/flexible working practices can be expressed on several levels. Flexibility is sought in part for the individual worker's tasks, workplaces, and working postures. In a broader sense, flexibility refers to groupings within a department or working location, and finally as a simple means for altering activities within the building.

flexible office An office designed for flexible work practices; that is, a workplace (including chair, desk, IT-equipment, and associated furniture accessories) that is utilized by different people at different times.

flexible employment forms Different ways for a company to purchase competence without necessarily hiring people in the usual manner. Flexible work practices can include project employment or contracted labor.

flexible office layout An office without permanently constructed dividers and fixtures, where quick alterations are permitted.

flexible work hours Flexibility regarding work hours in relation to daily, weekly, monthly, or annual work hours.

flexible work practices The concept of flexible work practices means deviations are made from the "traditional" method of binding work practices to time, place, methods, tools, and organizational identity.

Furniture

adjustable table Tables that can be raised and lowered (sitting—standing) are available in several varieties. The common models are the balanced (load-dependent) table and electric table. The balanced table is one in which the adjustment depends on springs and counterbalances that are set (balanced) against the load that the table bears. With an electric work table the adjustment is made with the help of an electric motor.

personal storage Either a movable personal storage (usually in rolling cabinets) or a permanent personal storage located in a designated shelf or cabinet.

rolling cabinet A personal storage cabinet on wheels, produced for an office with flexible workstations. Contains storage space in the form of drawers and shelves, as well as a collapsible table surface on certain models.

rolling closet A personal closet on wheels, produced for an office with flexible workspace. It looks like an ordinary domestic closet into which a rolling cabinet can be rolled. It also includes space for personal effects such as clothing, shoes, and so forth.

Room Concepts

alternative office workstations An alternative place where work can be carried out, apart from the normal workstation. This can be a workstation developed for sitting/standing work positions. A person who sits with a laptop at a coffee table or who has a telephone conversation in the "quiet room" is using an alternative office workstation.

cabinet garage Area intended for "parking" rolling cabinets when they are not being used by their owners.

project room A room for temporary project work.

project workstations Workstations specially adapted for executing project work within groups of varying size.

quiet room Area or room intended for temporary use by one or more people. This type of room can also be used for private telephone conversations, and so forth for those who sit in open areas. The criterion for this room is that it cannot be reserved; it is available for spontaneous use.

Miscellaneous

business process analysis Analysis of business processes carried out in such a manner that the results can be used to design workflow and methods. Business process analysis is based upon questionnaires and interviews, in addition to practically conducted work sessions.

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BIOGRAPHIES

Tomas Berns, PhD., who received a bachelor's degree in engineering in 1967, a master of science degree in 1972, and a doctor of philosophy degree in ergonomics in 1990 at Lougborough University of Technology, England, is an ergonomics/human factors specialist working with research and consultancy, primarily in the area of information technology. He is a founding partner and the president of Nomos Management. Since 1993 he has been chairman of the SIS (Swedish Standardization) working group responsible for ergonomics of human system interaction, including work on ISO 9241, which deals with both hardware and software issues. He is a member of several international working groups within ISO TC159 Ergonomics. From 1993 to 1997 he was chairman of the Swedish Ergonomics Society and on the board of the Nordic Ergonomic Society.

ERGONOMICS IN THE OFFICE ENVIRONMENT

Lars Klusell is a professional ergonomist (human factors specialist) who has been a consultant and researcher since 1971, primarily in the areas of workplace environment and workplace design. Lars started his career at the Swedish National Institute for Occupational Safety and Health, where he reached a position as senior research engineer in ergonomics. He subsequently held a position as safety and hygiene engineer at the Swedish Post Office, and in the mid-1980s, moved to Philips Information System as human factors specialist. At Philips (later Digital Equipment BCFI AB) he was responsible for all ergonomic activities, both in product design and customer relations. During the two last years at Digital, he held a position as project manager for the Digital concept “Office of the Future.” Lars joined Nomos Management AB in 1994.

Source: MAYNARD'S INDUSTRIAL ENGINEERING HANDBOOK

CHAPTER 6.6

THE INTERFACE BETWEEN PRODUCTION SYSTEM DESIGN AND INDIVIDUAL MECHANICAL EXPOSURE

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This chapter deals with methods for considering ergonomic aspects when designing production systems.* Ergonomic techniques that can be applied by engineers are briefly reviewed, as well as some engineering methods with ergonomic potential. Examples are provided to show how engineering and ergonomic methods may be combined in production system design.

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* All authors belong to the Swedish network COPE (Cooperative for Optimization of Industrial Production Systems Regarding Productivity and Ergonomics).

BACKGROUND: MUSCULOSKELETAL DISORDERS AND MECHANICAL EXPOSURE

Musculoskeletal complaints and disorders represent a significant problem in working life all over the world. These disorders not only cause human suffering, but also lead to economic losses, which (depending on insurance systems) may to a varying extent fall on the company. The work-related fraction of the musculoskeletal disorders (i.e., the fraction that could have been avoided by changing to risk-free work) is assumed to be about 40 percent. Thus, health has become an important issue to consider when designing production systems, particularly in cases where individual workers are not easily interchanged.

Jobs that include manual lifting mainly carry a risk of developing low back disorders, while repetitive work (e.g., handling of light materials/components) mostly gives rise to disorders in the shoulder-neck and arm-wrist regions. The origin of work-related musculoskeletal disorders is multifactorial and complex, involving both physical and psychosocial factors and the capacity of the individual worker.

This chapter focuses on the physical workload (i.e., the *mechanical exposure*) as opposed to other physical exposures like noise. Comprehensive research [1] has indicated that three dimensions of mechanical exposure are important to the risk of acquiring disorders: (1) level (or amplitude), (2) duration, and (3) repetitiveness (or frequency). Exposure may be described in terms of external factors (e.g., by stating the weight of products to be handled, the average productivity demands, or the duration of normal working days). This approach is useful in the design process since it focuses on issues influenced by the engineer in the design of the production system and is independent of characteristics of the workers entering the future system. Moreover, it is compatible with common engineering tools, as demonstrated shortly. When an individual performs a certain external task using his or her particular working technique, forces are developed in muscles and bones, and this so-called internal exposure, combined with the capacity of the individual, determines whether a disorder develops. A major goal for the ergonomist and the engineer is to be able to translate external exposures (e.g., task descriptions) into internal exposures (e.g., muscle load). A prerequisite for achieving this goal is the ability to express mechanical exposure in terms and entities compatible with engineering and predictive of internal exposures. Thereby the exposure may be predicted even in imaginary production systems. To a large extent this approach is new to the ergonomist, and some of the framework described here is still under development.

The aim of this chapter is twofold: (1) to present some existing ergonomic methods that may be used by the engineer to predict mechanical exposure and (2) to suggest an approach for combining ergonomic and engineering methods.

SOME ERGONOMIC METHODS IN PRODUCTION SYSTEM DESIGN

Anthropometrics in Workplace Design

By use of anthropometric data (Fig. 6.6.1), the physical dimensions of a workplace can be matched to human requirements. Anthropometric data for different populations may be found in the literature (e.g., [2, 3]). In addition, sets of drawing templates exist to help the workplace designer. Anthropometrics is often used in workplace design to create a healthy workplace and to increase efficiency.

The use of anthropometry may result in a well-designed workplace from a static viewpoint. *Dynamic* anthropometric data (e.g., concerning functional strength in different body regions) may also be included [4]. However, these procedures are directed only toward the exposure level and do not consider the duration and repetitiveness of the work performed.

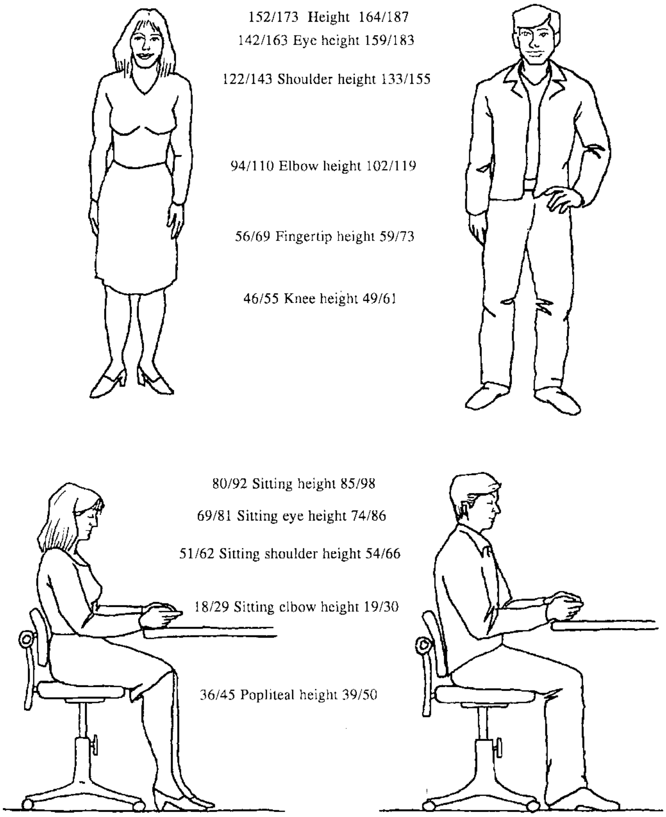
152/173 Height 164/187
142/163 Eye height 159/183
122/143 Shoulder height 133/155
94/110 Elbow height 102/119
56/69 Fingertip height 59/73
46/55 Knee height 49/61
80/92 Sitting height 85/98
69/81 Sitting eye height 74/86
51/62 Sitting shoulder height 54/66
18/29 Sitting elbow height 19/30
36/45 Popliteal height 39/50

FIGURE 6.6.1 Anthropometric measures for average U.S. adults (5th/95th percentiles for women and men, in cm).

Biomechanics

In simple biomechanics, methods from mechanical physics are applied to the human body. It may be seen as an extension of anthropometrics, since it combines information on external loads with data on body dimensions and posture (see Ref. [4]). Methods for assessing body postures will be reviewed subsequently. Simple biomechanical models provide estimates of loads and torques to the body that may be useful in assessing ergonomic demands. In principle, biomechanical data can be obtained continuously during a work operation as a basis for assessing the level, duration, and repetitiveness of the exposure. Most often, however, biomechanical calculations are restricted to snapshot situations that are considered to be representative. In this case, only the exposure level is obtained. More elaborate biomechanical models that predict the activity in individual muscles during work have been developed. So far, however, these techniques are complicated and of questionable practical value.

Checklist Methods

Workplaces may be designed and evaluated by use of checklists [5]. Many checklists are intended for trained ergonomists, however, and may be less useful for engineers without ergonomic experience. The Nordic Council of Ministers has published a model for evaluation of exposure [6]. Figure 6.6.2 presents the checklist for repetitive work.

Checklists may be a valuable tool for highlighting ergonomic problems, but normally are not useful at a detailed level. The checklist presented in Fig. 6.6.2 incorporates the three dimensions of level, duration, and repetitiveness in a way that makes it superior to many other ergonomic checklists.

Computer-Aided Design (CAD) Models

During the last 10 years many computer-based mannequin models have been developed [7]. Some of them are discussed elsewhere in this book. The mannequins are based on the same anthropometric data as may be found in printed tables, but they offer many advantages. Most important, the mannequin may be integrated in an ordinary CAD drawing and included in the visualization of the final result. Another advantage is the option of incorporating biomechanical evaluations in the program. As in the case of classical anthropometry and biomechanics, a drawback is that most programs consider only the static mechanical exposure level, disregarding the aspects duration and repetitiveness.

Task Analysis

Task analysis is a common procedure in ergonomics, as it is assumed that different tasks are associated with different mechanical exposures. Thus, the job exposure of an individual worker, or *product cycle exposure* (see ergonomic terminology later in this chapter), may be assessed by decomposing the product cycle into well-defined tasks with known exposure. The assessment of the prevalence, frequency, duration, and distribution of different tasks may be accomplished by observation techniques or by analyzing video recordings, or it may be made by the workers themselves (e.g., in a diary). Tasks may be categorized at different levels of

	Red zone	Yellow zone	Green zone
Working cycle	Repeated several times/ minute more than half of the day	Repeated several times/ hour more than half of the day	Repeated some times/hour
Postures and movements	Fixed or uncomfortable	Limited possibilities to alter	Good physical layout and good possibilities for variation
Freedom of action	Completely governed by something or somebody else	To a certain extent governed by something or somebody else. Limited possibilities to influence work performance	Good possibilities to fit the work to one's own ability. Influence on planning and organizing of the work
Work content learning	One isolated task in a production process. Short training time	Several tasks in a production process. Job rotation may be present. Training for different work areas	Several tasks or a complete production process including planning and control. Competence develops continuously

FIGURE 6.6.2 A checklist proposed by the Nordic Council of Ministers for evaluation of exposure in repetitive work for a complete workday. Work mainly characterized by the red zone (left column) is regarded as unacceptable. Work within the yellow zone (middle column) should be further evaluated, and attempts should be made to redesign the work to comply with the descriptions in the green zone (right column).

THE INTERFACE BETWEEN PRODUCTION SYSTEM DESIGN AND INDIVIDUAL MECHANICAL EXPOSURE

detail depending on the aim of the analysis. Different methods for assessing *task exposures* (see ergonomic terminology later in this chapter) and for combining task distributions with exposure information will be discussed subsequently.

Estimated Oxygen Uptake

A task analysis may be combined with data on energy demands in each task in order to estimate the total energy demand associated with a job. Task exposure data may be obtained from the literature (e.g., see Table 6.6.1 and Ref. [8]) and weighted according to the occurrence of the task in the job or product cycle. This method will consider repetitiveness only at a very crude level and is relevant only for heavy work requiring activity involving large muscle groups.

TABLE 6.1 Average Oxygen Uptake in Different Activities

Activity	Oxygen uptake, l/min
Rest	0.3
Driving, sitting	0.5
Walking	1.0
Lifting 10 kg	1.3
Fast walking, running	1.5
Heavy manual work	1.7

Direct Technical Recordings

Direct technical recordings (i.e., methods based on measurement devices fixed to the body) can be used if detailed information on mechanical exposure is required [9]. All three exposure dimensions—level, duration, and repetitiveness—can be assessed in this way, since direct methods can provide continuous recordings of exposure. Some of these methods are presented briefly here, and an application example combining direct technical measurements in the form of electromyography (EMG) with engineering methods is presented in the section Zero-Based Analysis.

Electromyography. Surface electrodes picking up muscle electricity can be used for assessing muscular load in field studies. Computer programs for signal quality control and normalization are available. Typical exposure variables are load distributions, durations of muscular rest, and patterns of load variation.

Goniometry. Joint angles (independent of gravity), for instance at the wrist, can be assessed by goniometers (angle transducers). By means of computer programs, it is possible to derive distributions of wrist angles and angular velocities, as well as power spectrums. These data, in turn, can provide information on extreme positions, median and peak velocities, and measures of repetitiveness. Information on joint angles can also be obtained by optical systems. For example, reflectors are placed on the body and followed on a videotape.

Inclinometry. Angles of body parts relative to the line of gravity are measured as an expression of working postures, using transducers based on pendulums or electrolyte solutions. A common approach is to arrange two inclinometers perpendicular to each other to get angles in the three-dimensional space. Dynamic accelerations can be assessed by accelerometers, which will also provide information on positions and movements of, for example, the head, back, and upper arms.

All of the preceding methods can produce a continuous series of raw data. These data may be temporarily stored on different media (e.g., tape recorders or data loggers). Data loggers are particularly useful in work settings, since they leave the subject free to move and work and are less sensitive to disturbances than other methods.

PRODUCTION ANALYSIS METHODS WITH ERGONOMIC INFERENCES

The methods reviewed thus far have been developed for ergonomic purposes. They may also, however, be accessible to the engineer and compatible with engineering tools. This section deals with methods developed by engineers to increase efficiency in production systems. At the same time, however, the methods may be powerful instruments—or become so in the future—for assessing mechanical exposure, or they may be combined with the aforementioned methods to consider efficient production systems and good ergonomics simultaneously. Two major lines of development may be fruitful: approaches related to the time consumption and a new approach utilizing product structure information.

Zero-Based Analysis

One method for designing production systems is the so-called zero-based analysis [10], originally based on work by Wild [11] in which performance aspects of the assembly line were quantified.

Traditionally, engineers use mean operation times based on time-and-motion studies when determining work cycle times and do not pay sufficient regard to the effects of the variation between and within workers in pace and efficiency when performing repetitive work. Furthermore, the amount of work to be performed at each workstation will vary between work cycles and workstations on account of differences in product variants. There will also be process variation caused by, for example, tools and mechanized equipment. These variations introduce losses into the production system in the form of rework, waiting times, extra space, low quality, and so on.

The principle of zero-based analysis is that the actual resource consumption (for example, in the form of human work) is estimated and, compared with the consumption required in an ideal production system, free of losses. Thus, this method highlights the important resources from a value-adding perspective. It allows a determination of rationalization potentials, as well as comparisons between different production system designs.

Zero-based analysis may be founded on different types of data, including *secondary data* (e.g., budget figures or figures from method-time measurement [MTM] analyses) and *primary data* (e.g., video recordings). In the latter case, the video-recorded work is decomposed into tasks and operations, which are then analyzed in terms of necessary and excessive time consumption. Since tasks and operations may be associated with known mechanical exposures, as outlined previously, the consequences of intervention may in principle be predicted by combining the mechanical exposures of tasks remaining after, for instance, a change.

Predetermined Time Systems

Predetermined time systems (PTS), for example MTM, have been developed to assess the duration of work operations and tasks on the basis of movement times. Since, however, several of the factors influencing the duration of movements (e.g., distance and object weight) are known also to affect mechanical exposure, it seems reasonable to expect that an MTM categorization may also produce valuable ergonomic information. Preliminary studies have indicated that this is indeed the case. In addition, work pace as quantified by an MTM analysis has been shown to influence mechanical exposure—a higher pace giving larger exposure levels and faster load changes. On the other hand, several factors known to influence exposure are not taken into consideration in the MTM system (e.g., working height). Thus, more diversified PTS, including operation categories with an ergonomic rationale, might become a powerful and easy tool for ergonomic assessment of systems in the planning phase. A similar idea has been adopted in the ErgoMOST system, in which ergonomic information quantifying and evaluating the stress of operations is linked to the MOST analysis [12].

Integrating Ergonomics and Product Structure Information

The basis of the manufacturing process in automotive companies consists of an overall product structure. The product structure is the result of development efforts in the design department, which traditionally do not sufficiently consider the needs of the specific final assembly system, since, among other things, these plants may manufacture different products and also may have various production system designs. The engineers therefore transform the information contained in the product structure to suit the local plant. Especially in systems with assembly work with a long cycle time, an assembly-oriented product structure is required, based on the generic characteristics of the product instead of, as is traditional, on a market- and design-oriented product structure.

However, the product structure information might also be of ergonomic interest, since it includes latent information on mechanical exposure (component weights, assembly positions of the product, torques, etc.). This possibility has not yet been explored, but seems promising from our studies in the automotive industry.

In the future, benefits in terms of efficiency and ergonomics could be gained by overcoming the traditional barriers between assembly plants and design departments. The interaction could lead to the designs allowing ergonomically advantageous variations in work both within and between individuals.

ERGONOMIC TERMINOLOGY ADAPTED TO PRODUCT SYSTEM DESIGN

Hitherto, ergonomic terminology has been suggested by ergonomists without inclusion of aspects of production system design. In order to integrate ergonomics with production, it is important to develop a terminology acknowledging both issues. The design process of a production system may be viewed as a number of partly interconnected decisions, resulting in gradually more concrete and detailed descriptions of the final system (Fig. 6.6.3). Examples of decisions at increasingly detailed levels are (1) product description, (2) efforts needed to accomplish production (e.g., the contributions of assembly and white-collar work), (3) allocation of work to either manual labor or machines according to the technological level of the production system, and (4) design of work processes, which are (5) subdivided into tasks (e.g., comprising few or many elementary operations) and (6) distributed between individuals.

Each of these decisions must comply with constraining factors both outside and inside the company (e.g., rules and regulations of the society, finances, and competence of the workforce). As the design process goes along, the number of possible final realizations of the production system design is reduced. Accordingly, the degrees of freedom for obtaining varying mechanical and psychosocial exposures of the workers are gradually decreased. The term *exposure latitude* has been suggested to express the flexibility of the production system—at any stage of concretization—in generating different exposures of the workforce [13]. As an example, the exposure latitude in a traditional tayloristic system may be expected to be low, since work processes are controlled/predetermined to single movements and distributed

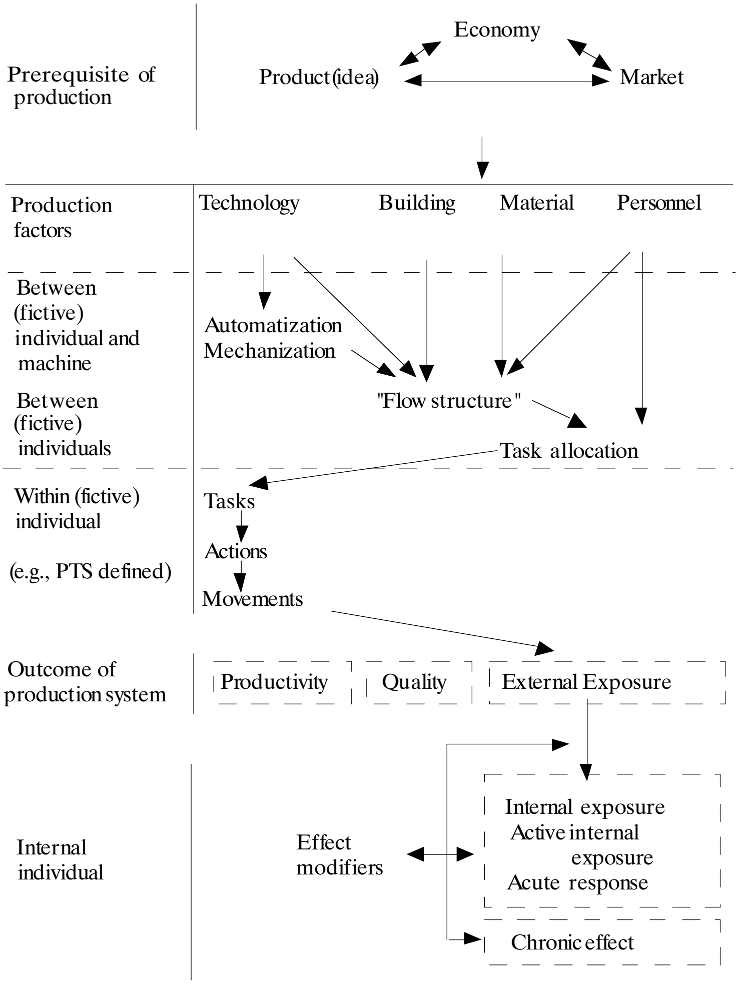
Prerequisite of production
Economy
Product (idea)
Market
Production factors
Technology
Building
Material
Personnel
Between (fictive) individual and machine
Automatization
Mechanization
"Flow structure"
Between (fictive) individuals
Task allocation
Within (fictive) individual
(e.g., PTS defined)
Tasks
Actions
Movements
Outcome of production system
Productivity
Quality
External Exposure
Internal individual
Effect modifiers
Internal exposure
Active internal exposure
Acute response
Chronic effect

FIGURE 6.6.3 A conceptual model of the production system, describing the relationship between production factors and the resulting exposure of the individual workers [14] (PTS = Predetermined Time Systems).

among individuals according to strict principles of specialization. When a production system gradually takes shape according to the traditional chain of decisions, exposure latitude is likely to diminish. An important goal for the designer of the production system would be—in cooperation with ergonomists—to retain system layouts offering both high productivity and good ergonomics.

The exposure latitude of a production system may be expressed in quantitative terms only if the mechanical exposure generated in the production system is assessed. The term *product cycle exposure* denotes the average exposure associated with one product. *Product cycle* may be defined according to the preference of the engineer (e.g., with or without inclusion of complementary tasks, transportation, and idle time), but the term refers basically to the actions associated with producing one complete product. In this respect, the concept of product cycle exposure is compatible with loss zero-based analysis techniques [10].

THE INTERFACE BETWEEN PRODUCTION SYSTEM DESIGN AND INDIVIDUAL MECHANICAL EXPOSURE

As in the zero-based analysis, an assessment of product cycle exposure is based on a decomposition of the production process into tasks with known exposures. The task exposures occurring during the product cycle may then be evaluated according to their relative duration in the cycle. An example of a combined loss and ergonomic analysis will be presented shortly. The tasks or task categories may be specific to the production system in question (e.g., "fetching component 2314," "lifting from band to pallet"), or they may be transferable between industries (e.g., "manual transport of boxes," "truck driving," "lunch break"). Product cycle exposure may be predicted in future production systems by using available exposure data for the relevant tasks, in combination with their planned distribution and duration. Thus, information on task exposures must, at least in theory, be available for all tasks that might appear in any production system, including the consequences of performing tasks in different ways (e.g., at different paces of work or with different degrees of losses). The exposure associated with new or radically altered tasks cannot be assessed in a running plant and may have to be estimated by ergonomic methods in a mock-up or by use of existing engineering tools for task description.

ILLUSTRATIVE EXAMPLES

Utilizing Product Structure Information for Describing Assembly Work

In a study at an automobile assembly plant, the work of nine assembly workers was analyzed by differentiating between (1) pure assembly work, consisting of fitting of specific components, and (2) connecting already fitted pipes and cables. The pure assembly work may bear a direct relationship to the product structure information, since specific components are assigned to specific work tasks through the bill of materials. The connecting work, on the other hand, does not offer this possibility. Figure 6.6.4 presents the work of four of the nine workers studied.

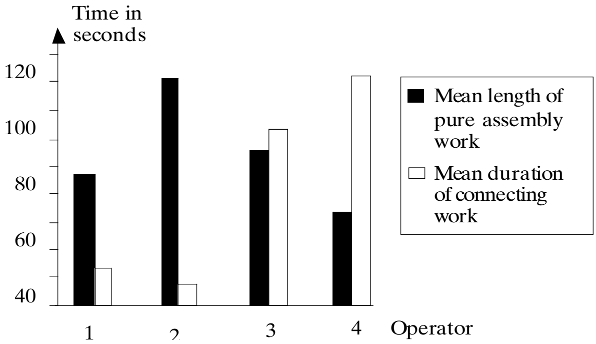

FIGURE 6.6.4 The work contents of four workers performing assembly work in an automobile assembly plant. Pure assembly work: fitting of specific components; connecting work: connecting already fitted pipes and cables.

Differences in work contents between the beginning and the end of the assembly work were clearly evident. The pure assembly work at the start of the process is characterized by the fitting of discrete components, which usually requires an exact torque to achieve the correct quality. The connecting work at the completion of the vehicle, on the other hand, is characterized by adjustment of interrelated components to correct tolerances. This work is related more to cosmetic demands. It was also evident that the initial work is fragmented into short work bursts, while the finishing of the vehicle involves relatively few but coherent work tasks. This insight illuminates the possibility of using the product structure information to describe the assembly work by considering whether, for example, discrete components are fitted or not. If this method were developed further, the work tasks might be balanced between the workers to achieve more favorable individual ergonomics.

MTM and Mechanical Exposure at a Sewing Machine Assembly Plant

In a study at a sewing machine assembly plant, Bao et al. [13] had access to the company's MTM analysis of work operations, expressed in the Swedish SAM system (sequence-based activity method). The authors used this information directly to quantify the time proportions of different types of actions during work (e.g., back-and-forth movements, operations requiring precision, and forceful actions, as defined in SAM). This resulted in exposure estimates, both for each separate workstation and for the complete production system. The latter corresponds to the product cycle exposure as defined previously. The study was conducted by intervening in the production system, which according to the company should lead to increased flexibility in production and also to better ergonomics. The stations in the new system differed from the old with respect to mechanical exposure, and the new production system contained fewer actions requiring force than the old system.

Thus, the new system seemed to have a potential for offering better ergonomics to the workers than the old one (i.e., it had a better exposure latitude). However, contrary to the intentions of the company, workers did not change workstations very often and therefore retained a quite monotonous, short-cycle job. Thus, the exposure latitude was diminished in an unfortunate way when work was distributed between individuals. These findings were confirmed by more elaborate and direct measurements of mechanical exposure. These experiences indicate that PTS ratings in themselves offer information that may be sufficient to evaluate the ergonomics in industrial production systems at a coarse level.

Zero-Based Analysis Integrated with Ergonomics

A case study was conducted at an assembly plant producing about 1500 specialty automobiles a year. It focused on supply of materials for assembly of individual specimens of special vehicles (e.g., police automobiles, taxis, and limousines). The work mainly comprised (1) kitting of materials by positioning components in a plastic container placed in a long row, (2) picking of small components into subkits, and (3) picking of materials from a store, using an order-picking truck. The workers were video-recorded and the work was subjected to task decomposition and analysis according to zero-based analysis techniques. At the same time, data on mechanical exposure were collected by EMG, and the mechanical exposure associated with each task was determined. Specifically, the duration of *muscular rest* (i.e., muscular activity below 1 percent of a maximal effort) was assessed. The principal results are presented in Fig. 6.6.5. The relative duration of rest was markedly longer in administrative work than in "necessary" work. Thus, if the company decides to reduce administrative tasks and increase necessary work, the muscles may encounter fewer rest periods. A reduction of rest periods may lead to increased risk of musculoskeletal disorders, as found in previous studies.

FUTURE TRENDS

One of the most important issues for the future seems to be the development of suitable methods for the engineer (an easy-to-use toolkit) that would enable him or her to predict the mechanical exposure as a natural part of the design process of a production system. Some of the ergonomic methods described in this chapter may be used as they are, or they may bene-

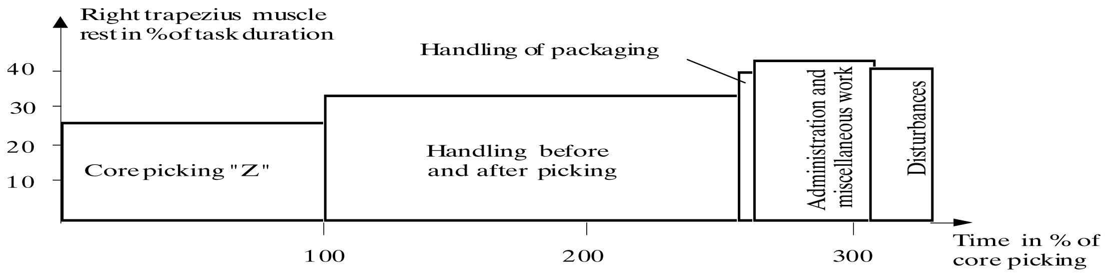

FIGURE 6.6.5 Zero-based analysis and trapezius muscle rest in materials kitting. *Muscle rest* is defined as muscular activity below 1 percent of maximal effort. The figure illustrates that different activities in the job are associated with different exposures and that an intervention against losses may change the exposure.

fit from further development. Originally, they were created to suit the ergonomist rather than for use by the engineer for predictions of mechanical exposure.

It also seems important to develop ergonomic approaches that utilize methods and information already available to the engineer. We are convinced, for example, that the information contained in the product structure could also be used for ergonomic purposes.

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BIOGRAPHIES

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Tomas Engström has been associate professor and head of the Materials Handling Research Group at the Department of Transportation and Logistics at Chalmers University of Technology since 1978. He holds an M.Sc. in mechanical engineering and a Ph.D. (1983). His work has resulted in development of new materials feeding techniques, layouts, materials flow structures, and work structuring principles for long-cycle-time assembly work implemented in, for example, the Swedish automotive industry.

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Source: MAYNARD'S INDUSTRIAL ENGINEERING HANDBOOK

CHAPTER 6.7

HUMAN-MACHINE SYSTEM DESIGN AND INFORMATION PROCESSING

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Industrial studies done at the start of this century might be considered human factors research today. However, it is primarily since the mid-twentieth century that researchers have systematically addressed the issue of how humans can be best integrated with machines to maximize safety and task performance. Human factors engineering research has demonstrated that molding the machine to the human is far more effective than molding the human to the machine. This field of science has attracted engineering and psychology researchers, yet it has drawn less attention from engineering practitioners. The historical focus of engineered systems development has been on technological resources and physical characteristics of the task environment. Human factors as a discipline has often fallen by the wayside in the design process. There remains a need to impart human factors research findings into human-machine systems development. This chapter emphasizes the importance of human factors considerations in design through examples of human-machine system performance. New methods of human-machine integration will also be presented.

INTRODUCTION

People have been trying to develop new and improved tools since prehistory. This activity began to evolve into a scientific discipline around the start of the present century with work by F. W. Taylor and the Gilbreths. For example, the well-known system of arranging surgical instruments on a tray in a fixed fashion and having a nurse-assistant place them into the surgeon's hand is one of the latters' innovations. Those early efforts are properly part of the development of industrial engineering. Human factors per se developed from the application of psychological knowledge and practices, as opposed to management or engineering methods, to the same study of work. Although this has its earliest antecedents in ideas like Taylor's scientific management, it is really since the middle part of this century that the discipline of human factors began. Since that time, human factors researchers have attempted to systematically address the issue of how a human can be best integrated with machines to maximize safety, effectiveness, and efficiency.

Human factors focuses on applying knowledge of human physical and information-processing capabilities to designing systems so that machine configuration can adequately support the mission of the human user. This is sometimes called *user-centered design* to acknowledge that design starts with the *human's* mission rather than with finding ways to shoehorn human operators into a *machine's* mission. Human factors also includes testing machine prototypes and developing training protocols to teach human operators how to work with a system.

This chapter concentrates on traditional human factors issues related to helping users understand the systems they use and providing them with more usable systems. These directions of research are loosely captured by the labels *human factors engineering* and *cognitive engineering,* which are fields of science that have only recently been formally defined [1–3]. Human factors engineering involves user-centered design of the human-machine relationship, physical workspace, and training systems. Cognitive engineering is a subfield of human factors that concentrates on system comprehension and human decision making. Human factors research has demonstrated that molding the machine to the human is more effective than molding the human to the machine in both the short and long term.

Although human factors engineering has attracted researchers in industrial engineering and psychology for several decades, the established and developing tenets of the discipline have drawn less attention from engineering practice. The focus of engineered systems development has been primarily on the technological resources available and their capabilities, as well as the physical characteristics of the task environment in which the system is to function. The physical and cognitive aspects of the human have often fallen by the wayside in the design process, as has the training subcomponent of human factors engineering. Ironically, the outcomes of engineering practice have been the motivators of the majority of system designer and developer concerns with human factors engineering. Numerous disasters involving human-machine systems, including the nuclear accident at Three Mile Island in 1979 [4] and the catastrophic crash of a Northwest Airlines MD-80 at Detroit Airport in 1987 [5], have underscored with a broad stroke the need for consideration of human characteristics in the system design process. These incidents demonstrated the critical flaw of technology-centered design of human-machine systems. Unfortunately, these types of accidents continue to occur due to this critical flaw in the traditional system design process, as illustrated by the crash of an American Airlines 757 near Cali, Columbia, in 1995 [6]. That crash resulted from pilot misinterpretation of terrain proximity through interaction with an automated flight management system. Consequently, there remains a dire need to impart the findings of human factors research into human-machine systems development to ensure successful performance.

The goal of this chapter is not to detract from the importance of technological and environmental issues in the systems design process, but rather to establish the importance of human behavioral issues. This is accomplished by discussing the system design process in general and providing examples of how the results of human factors research can be effectively applied in the development of human-machine systems. Methods of human-machine integration offering advanced solutions to system safety and performance challenges will also be presented. This chapter concentrates on human information processing issues in systems design and examines strategies for blending the human and machine in automated systems control and task performance through human-centered systems design that considers aspects of cognition, including situation awareness (perception, comprehension and projection), and mental models. Task, environment, and system-driven influences on cognition, including mental workload, are also considered. In particular, rational function allocation for optimizing normal and failure-mode operations, based on both human and technological capabilities, are discussed with reference to seminal research on level of control. Additionally, human-machine system interface (display and control) design issues are discussed, and the results of perception and action selection research in, for example, teleoperation, aviation, and process control systems are presented. Finally, the chapter provides insight into advanced human factors engineering methodologies for dynamically manipulating the human-machine relationship to optimize performance across time under varying task and environmental conditions, including adaptive automation.

BACKGROUND

Human versus Machine

Historically, one central job design issue has been whether a human or a machine should perform a particular task. Humans are more flexible and more capable of interacting meaningfully with the environment, especially if it is unstructured or dynamic, but machines are stronger and more accurate. Three decades ago, Jordan [7] said, "[people] are flexible but cannot be depended upon to perform in a consistent manner whereas machines can be depended upon to perform consistently but they have no flexibility whatsoever." The advent of artificial intelligence has not made this observation obsolete. Modern human-machine systems often depend on automated systems (including robots) to perform routine tasks under human supervision, as well as to direct human intervention for nonroutine tasks and in response to unanticipated events [8]. Norman [9] has noted,

> As automation increases, the need to apply such [ergonomic design] principles becomes more urgent. . . . Workers who operated tools could view many of the parts and could see the effects of their actions. People had some hope of understanding how large machinery and small gadgets worked, because the parts were visible. The operation of modern machines and the concepts behind their design are invisible and abstract. There may be nothing to see, nothing to guide understanding. Consequently, workers know less and less about the inner workings of the systems under their control, and they are at an immediate disadvantage when trouble erupts.
>
> Such alienation has startling effects: most industrial and aviation accidents today are attributed to human error.

As Karwowski et al. [10] point out, new technologies will require more from users than old technologies did. New technologies require design with the contribution and capabilities of workers planned into the system a priori. Corbett [11] lays out some principles for human-centered job design. Human-centered design (1) accepts human skills and allows them to develop rather than minimizing human contribution; (2) allows users to modify their own goals and behavior; (3) "unites the planning, executing, and monitoring components" and avoids the extreme specialization of conventional manufacturing; (4) encourages coordination and communication between workers; and (5) provides "healthy, safe, and efficient" working environments. These principles might be termed *skills utilization, job flexibility, job integration, coordination,* and *ergonomics,* respectively. Grote et al. [12], in an analysis of function allocation in advanced manufacturing systems, list five criteria for success: (1) coupling, which has to do with the integration of human and machine; (2) process transparency/proximity, which has to do with how well the worker understands machine operations; (3) decision authority; (4) flexibility, which is similar to job flexibility; and (5) technical linkage, which has to do with how closely the machine is linked to other systems in the manufacturing process.

The Human Factors Function

Human factors is a contributor to the general twentieth-century goal of developing new technology, that is, new tools for people to use. It has a special role in that it is concerned with developing the usability of new tools, whereas other engineering disciplines are primarily concerned with the usefulness of new tools. Both contribute to efficacy. Human factors contributes by applying what is known about human performance (e.g., the functioning of human perception and human cognitive capabilities) to improve specification of new systems and by applying ergonomic principles to designing human-machine interfaces. The human factors contribution is made through four key components of the human factors function: analysis, design, training, and research.

Analysis. Analysis takes two forms: high-level evaluation of the requirements of an integrated set of activities or low-level recording of the actions taken to complete some task. The former may be called *mission analysis,* and it uses a top-down, reductionist approach to identify the functional requirements of some goal-directed set of behaviors. The latter may be called *task analysis,* and it uses a bottom-up approach to develop an understanding of user actions during execution of goal-directed behaviors. Both are essential in their proper context, and both support the design and research functions. Mission analysis is most useful for developing new technology because it concentrates on functions (i.e., what must be done). The results of mission analysis can be used to identify functions that can benefit from technology development or functions that are amenable to automation versus human control. Task analysis is most useful for developing work methods or for refining existing technology because it concentrates on how things are done. Both can support development of training programs.

Design. Design is the fundamental mission of human factors. The human factors contribution to design should start at the beginning of system development, when specifications are developed. The human factors contribution here should be to help identify the capabilities people need for filling roles within a system or to identify human needs for tools within the system mission. Early integration of human factors expertise into system design allows for the best possible integration of people into systems and allows the detailed design of controls and displays, workstations, and procedures to flow from the knowledge of how people fit. This is expanded upon in the next section, Engineered Systems Design.

Design should include not only the design of workstations, but also of systems. Human factors should contribute to system specification, not just develop displays and controls. Human factors should help lay the foundation for systems, not just put in place the capstone.

Training. Training program development is part of the systematic integration of humans into systems. Training begins with training needs analysis, which identifies characteristics of the expected user population and the performance requirements of the system mission. With that information in hand, it is possible to develop a curriculum that brings user knowledge, skills, and abilities into line with mission requirements. Training materials, simulators, and so forth must be developed from a sound perspective on human learning. They must also be ergonomically sound themselves.

Research. Human factors research is a form of experimentation aimed at quantifying human behavior within the context of technological systems or quantifying the impact of systems on users. It may be conducted to enhance understanding of human performance, with the aim of improving system design, or it may be conducted to assess the quality and efficiency of system designs. It is fundamentally an exercise in behavioral science and must make use of experimental and statistical methods developed in psychology and engineering. For some time in the history of human factors, methods were primarily generated from experimental psychology and concentrated on human perception and motor control. In more recent years, the emphasis has shifted toward cognitive engineering because of the increasing importance of human decision making, as opposed to energic interactions, in modern systems.

ENGINEERED SYSTEMS DESIGN

In order to establish the importance of human behavioral issues (e.g., sensory capabilities, memory capacity, and decision-making ability) in the systems design process, it is necessary to describe the traditional steps in engineering design. On this basis, avenues for human factors considerations in systems design can be identified.

Traditional (Technology-Centered) System Design

The approach of industrial engineers to engineering design through history has been a holistic one. The interactions between people, processes, machines, and tools have been examined primarily for improving productivity and product quality. This study has been focused on the physical and technical components of a system and their interactions. Human factors engineering design has occurred with significant contributions from the psychology and industrial engineering communities, which have developed knowledge on human behavior specifically for integration into engineering design principles.

As with industrial engineering, human factors takes an integrated systems approach to the design process, in which the specific interactions of the human operator with the machine, task, and environment are analyzed in terms of overall system performance. For the human factors engineer, overall performance includes the functioning of both human and machine. The objective is to optimize performance across both [13]. This is a shift in design focus from technical components to the human component.

According to Blanchard [14], the traditional steps in the engineering design cycle include (1) defining a need, (2) researching the need, (3) developing a conceptual design on the basis of feasibility studies and advanced system planning, (4) generating a preliminary system design and analyzing predicted functioning, (5) preparing a detailed system design based on prototype development and preliminary testing and evaluation, and (6) constructing the system.

Each of these steps is integral to the design process to ensure that a system is developed to meet defined performance objectives and quality considerations. To provide a simpler examination of this process, the steps can be categorized into larger design functions comprising (1) mission analysis, (2) technological analysis, (3) baseline system conceptualization, (4) functional analysis, and (5) implementation.

Wickens [15] has discussed these categories. Mission analysis includes any step in the design process involving establishing system objectives. Technological analysis is supportive of mission analysis in that it requires identification of current capabilities of automation with system objectives in mind. Baseline conceptualization extends beyond technological analysis by requiring identification of the minimum system characteristics required to accomplish the mission. Functional analysis describes the procedures to be employed by the system toward mission success and relies on technological analysis to identify automation needs facilitating the procedure. Functional analysis usually leads to identification of those aspects of the mission to be performed by machine.

An additional design function related to the human component is *function allocation,* which is an extension of the traditional design process identifying those system tasks that the human and/or machine are to perform. The previously discussed design functions essentially capture all steps in the traditional process. Function allocation with consideration of the human component has received little attention in the traditional, technology-centered process, but is prominent in human-centered systems design [15].

The relationships between the different categories of design steps are shown in Fig. 6.7.1, which also presents the traditional steps that fit into each function and the sequence in which they are addressed. The sequence places consideration of the human component at the close of the process, as a supplementary function.

Human-Centered Design

As discussed earlier, human factors issues need to be examined in all stages of the design process, starting with defining system needs through mission analysis. By considering engineering design recommendations based on human factors research in system definition and conceptualization, accommodation of an operator's characteristics and mission can be spread through the entire design process. Considering human factors in technological analysis is equivalent to conducting system functional analysis. Thus, the human-centered design

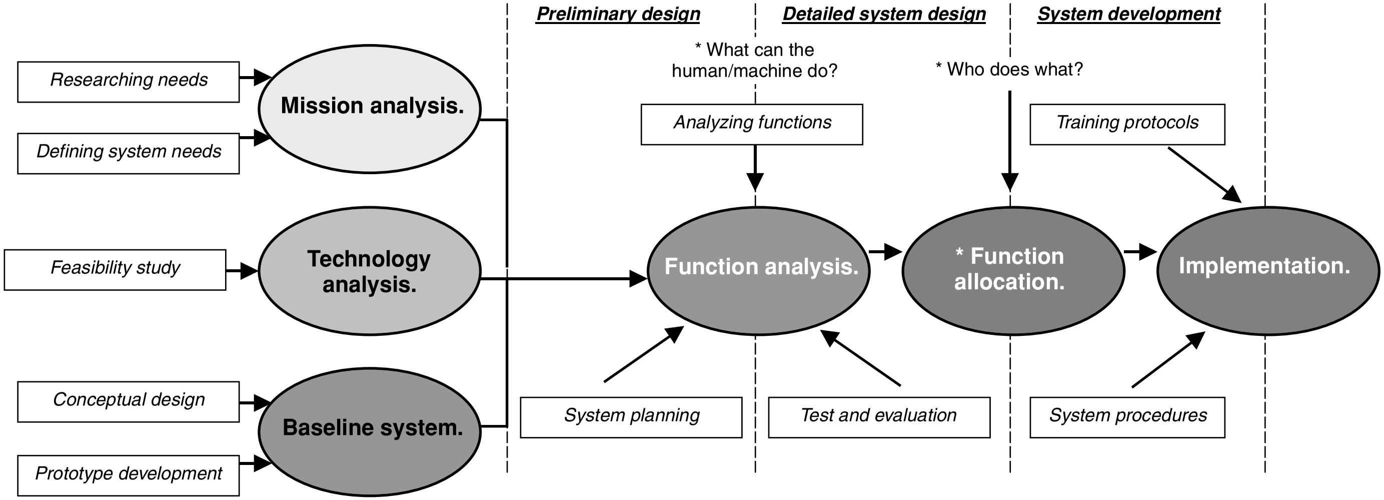
Preliminary design
Detailed system design
System development
Researching needs
Defining system needs
Feasibility study
Conceptual design
Prototype development
Mission analysis.
Technology analysis.
Baseline system.
* What can the human/machine do?
* Who does what?
Analyzing functions
Training protocols
Function analysis.
* Function allocation.
Implementation.
System planning
Test and evaluation
System procedures

FIGURE 6.7.1 Design steps and functions of systems design process.

approach may present a reduction in the number of steps in the technology-centered design process and facilitate a more integrated approach. In establishing a baseline conceptualization of a system, the most basic form of the system capable of accomplishing the mission is characterized. In technology-centered system design, a lack of consideration of the human in this step may promote unnecessary and costly automation. In addition, overspecification of automation in systems that require a human operator may promote problems in human-automation interaction due to operator boredom with limited roles in system control or general disinterest in the system. Incorporation of human factors considerations in functional analysis allows for identification of system functions that both humans and technology can perform. This information can be relayed to the function allocation step of the process as a general guide to who should do what. In this step, considerations need to be made regarding which functions the human or technology may be best at accomplishing. For example, automation is often designed to handle routine and mundane system operations involving high computational workloads. Such operations may promote human boredom and cognitive fatigue; thus, automation may be better adapted to these types of task. Humans are often superior to automation at decision making because of their ability to consider task contextual information. For example, expert systems or new technologies, such as neural networks, for adaptive control of robots are limited in decision-making capability by the sensor technology integrated with the robot (e.g., vision and haptics). These sensors do not approach human sensory systems in terms of accuracy, precision, flexibility, and adaptability in reflecting environmental conditions. Consequently, decision-making responsibility in integrated human-machine systems may best be left to the human. This is not, however, solely attributable to human perceptual capabilities but may also be accounted for by the capacity of humans to make fairly accurate decisions under time stress through the use of heuristics and biases. (These concepts will be discussed in detail later in this chapter under Decision Making and Performance.)

Figure 6.7.2 shows an integrated, human-centered approach to conceptual system design. The approach reflects consideration of human factors design standards and information on human capabilities in the design concept. It also presents inputs to the system design resulting from different steps in the traditional process, including prototype development and test and evaluation. As in technology-centered system design, there is a need to enhance conceptualizations based on prototype development and system testing against prescribed mission objectives. In the integrated, human-centered design approach, prototypical systems (or system simulations) are tested to determine their effectiveness in use. Overall system performance is evaluated, and the impact of system configuration on the human user is assessed. Outcome measures for testing are identified based on what is critical to system effectiveness. High performance, low operator error rates, low workload and operator confidence in performance may be important variables.

Other inputs in the system design conceptualization that may be unique to a human-centered approach include the need to look at human-machine information requirements for effective system functioning. These requirements can be useful in the design process, particularly in developing interfaces to promote human-automation interaction. (A detailed discussion of information analysis in automated systems design will follow shortly.) Analysis of information requirements supports both human factors and cognitive engineering in the design process. The information needs of a human operator may serve to guide system interface prototyping and, consequently, usability testing. The results of these tests can be incorporated in the overall process for enhancing design concepts. This is reflected in Fig. 6.7.2 as the input of different ways of designing the system interface on system conceptualization. Defining needed task information for mission accomplishment may also be useful in supporting operator perception of critical system data for decision making. Beyond motivating perceptual processes, information requirements analysis may serve to bring interface design into line with operator mental models of systems, promoting ease of use and overall performance. *Mental models* are mental pictures of systems around which users organize their perceptions and actions. Mental models guide the search for information and the meaning that is assigned

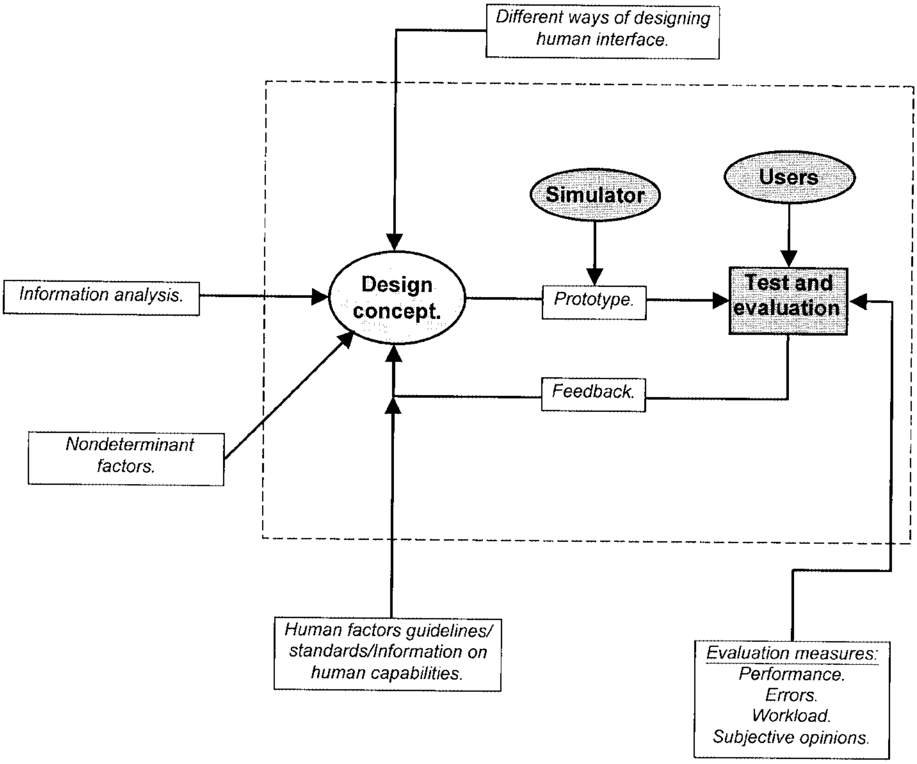
Different ways of designing human interface.
Information analysis.
Design concept.
Simulator
Users
Prototype.
Test and evaluation
Feedback.
Nondeterminant factors.
Human factors guidelines/ standards/Information on human capabilities.
Evaluation measures:
Performance.
Errors.
Workload.
Subjective opinions.

FIGURE 6.7.2 Integration of human factors considerations in conceptual design process.

to sensory data. Displays and controls that do not match the mental model are used inefficiently, and incorrect mental models may also lead to poor performance. In other words, users seek out information on the basis of their learned expectations of how the world operates. Problems happen when displays and controls don't match expectations or when expectations don't match the real-world system very well.

The integrated design approach also considers other variables that may indirectly affect system design, such as environmental conditions. By considering these factors in conjunction with human issues in the design process, system conceptualization can be optimized for overall performance.

HUMAN INFORMATION PROCESSING AND SYSTEM DESIGN

With roles in the engineering design process identified for human factors, the following question can be posed: Which human issues are critical in systems design and how do they affect different types of systems?

Physical Ergonomics versus Cognitive Ergonomics

Technology has evolved rapidly in the recent past. The emphasis of human factors has changed in response to changes in technology, now focusing more on human cognition.

Automation researchers (and others) have realized over the last three decades that technological considerations alone are often not sufficient to ensure the success of systems. Rather, the interaction between human and technology largely predicts results [16,17]. Cognitive issues have long been important topics in human factors, but design often concentrated mainly on physical ergonomics, such as the location of controls based on anthropometry [18] and their usability [19]. These considerations were largely sufficient for the design of systems that remained constant in their configuration throughout their useful lives. Most systems of 30 years ago operated under a fixed degree of autonomy: the role of the human operator was constant and the behavior of the technology predictable. Although cognitive ergonomic considerations may be important under these circumstances, for example, human understanding of the relation of control actions to system behavior, they received less attention in the past than they do today. This is partly due to a historical paucity of models of human information processing and performance data on varied task circumstances, as well as a perception that modeling human in-the-loop control of complex systems may not be feasible due to individual differences. An even more powerful reason may have been the simplicity, by today's standards, of the systems themselves. Increasing computerization and use of supervisory control make today's technology more difficult to understand.

Cognitive engineering has sought to address these challenges, as physical ergonomic considerations alone have not proved sufficient to optimize human interaction with new technologies such as expert systems. Artificial intelligence has provided automation with the capability of dynamic reconfiguration based on environmental circumstances, human operator actions, and other observable factors. The "glass cockpits" of newer commercial aircraft, including the MD-80, L-1011, and Airbus A-320, are good examples of such technologies and have revealed the need to apply considerations of human information processing in complex and dynamic systems design. For example, the design of digital cockpit displays to facilitate pilot perception of terrain characteristics and appropriate response execution has been a critical issue affecting aircraft safety. Air crashes due to pilots' failures to perceive (or misperception of) terrain warnings and aircraft altitude [15,20] on conventional cockpit displays while operating under high-workload conditions have demonstrated the need to develop interfaces that promote efficient and accurate human perceptual processing. Displays have been developed for advanced-technology aircraft to enhance human performance under taxing cognitive workloads by providing 3D views of the aircraft (versus 2D planar views with altitudes indicated in text format) [21]. Glass cockpit display research has demonstrated the former type to be far more effective than the latter in supporting vertical guidance tasks by pilots [22].

As another example of the need for cognitive engineering in technologically sophisticated systems, pilot comprehension of modes of aircraft control has also proved to be a critical safety issue. Advanced-technology aircraft, such as the Airbus A-320, have the capability of operating under varying degrees of human and autonomous flight control [23]. From a pilot's perspective, the functionality of cockpit controls, including thrust and flaps, may change from flight mode to flight mode. Research has documented failures of such systems due to a lack of mode awareness by the operator. To ensure proper operator performance, these systems require salient automation mode displays based on human information requirements and perceptual capabilities [24]. Unfortunately human cognition issues, like lack of mode awareness due to systems design, are not limited to aircraft, but occur in the use of everyday technological systems, including automobiles. For example, Andre [25] has noted problems of driver system awareness in regard to cruise control devices (e.g., forgetting that the system is active when approaching other vehicles or intersections). This work has further emphasized the need for cognitive engineering to enhance human-machine system performance.

As the state of any system changes, an operator's expectations about how the system should function also change, depending on his or her training, experience, and mental models. The role of the operator in the control loop may also need to be altered, with accompanying effects on aspects of cognition, including information perception and action processing. Physical ergonomics may sufficiently account for static automation configuration; however, cognitive engineering is requisite to deal with such effects in dynamic systems, including aircraft, advanced manufacturing systems, and process control.

Functional Analysis

The aspects of human cognition relevant to the design of complex systems are dependent upon several determinant factors, including (1) the goals of the system, (2) the task characteristics, (3) the functions to be maintained in pursuit of system goals, and (4) technological features. *Complex systems* are human-machine systems requiring operators to pursue multiple competing goals simultaneously under high task demands and limited time resources. In controlling such systems, the actions of an operator toward accomplishment of one goal may actually detract from another goal. The tasks to goal attainment usually involve higher cognitive processes, including strategizing with predicted outcomes in mind. Endsley and Kaber [26] studied a variety of complex, dynamic systems in an attempt to describe human-centered levels of automated control. They considered the roles of humans and machines in aircraft piloting, teleoperator control, process control, power plant operations, and so on, revealing a small set of generic functions maintained by a human operator and/or computer controller. These functions included monitoring, generating processing plans, selecting an optimal plan, and implementing the plan. Other human-machine roles in complex system performance have been identified in human factors literature regarding function allocation [27,28].

In functional analysis, as part of the engineered systems design process, we ask the question, "What aspects of human information processing are critical to successfully executing a function and system procedures?" The roles identified by Endsley and Kaber [26] involve aspects of human cognition including attention, perception, system or situation awareness (SA), and decision making. These may change based on the function being considered. To accurately identify system design requirements for supporting human information processing in maintaining a particular function, methods have been developed to relate overall system goals to aspects of human thinking. Endsley [29] developed and applied the methodology of goal-directed task analysis to different domains, such as air traffic control. This method involves (1) identifying goals of an operator or manager of a system, (2) defining detailed objectives for each goal, (3) determining major decisions to be made to meet the objectives, and (4) establishing information perception, comprehension, and projection requirements to permit decision making. The process establishes what an operator really needs to know about the system [29]. The information requirements developed from this analysis can serve as a guide to systems interface design supporting human cognitive processes.

Attention and Perception

Attention has long been considered to be an information filtering process [30] based on characteristics of environmental stimuli and factors internal to the human operator. Attention is the allocation of resources to processing inputs depending upon their characteristics and internal noise (e.g., failure of the senses). Attention may be *selective,* in which case certain inputs are processed (i.e., the subject of focused attention) while others are ignored. It may also be *divided,* in which case more than one set of inputs is processed simultaneously. Here we relate the modes of attention to human-machine system design.

Attention is the mechanism of human cognition defining information of importance to task processing and task distractions. It is largely directed by an operator's mental model of a system (i.e., his or her mental picture of dynamic system behavior). This is particularly true for selective attention, which is affected by mental model development as a result of operator experience. For example, aircraft pilot training is related to the ability to know where and when to look for a particular piece of information in the cockpit. According to Wickens [31], skilled pilots tend to look at areas of an aircraft instrument panel that change most frequently or provide the greatest information content. This behavior is not limited to visual attention, as humans also exhibit selective listening on the basis of information content and importance [32]. The implications of selective attention on systems design are summarized in Table 6.7.1.

TABLE 6.7.1 Selective Attention Needs in Signal Detection Tasks and Design Recommendations for Performance

Performance needs	Design recommendation
• Frequent and selective attention to multiple information sources on a single display.	• Minimize distances between information sources. • Minimize distances between sources that are related in an operator's mental model.
• Guaranteed perception of multiple stimuli.	• Train operators in task implementation strategies, including visual search patterns. • Use redundant encoding of stimuli across modalities (e.g., visual and auditory stimuli of a single system event).

A critical variable in the allocation of selective attention is the salience of information sources. Yantis [33] offered that salient information automatically calls attention to itself, thus facilitating selective operator attention. Increasing signal salience or intensity can serve to guarantee operator attention and perception [31]; however, salience of task distracters can serve to degrade focused attention. *Focused attention* is allocation of cognitive resources to a single information source while avoiding distractions. Focused attention, like selective attention, can be aided by making environmental stimuli discriminable from each other. Manipulating temporal and spatial characteristics of signals, as well as colors and sizes of targets, can encourage discrimination. For example, in air traffic management, a controller's job may be made easier by coding all aircraft within a specific altitude range using a single color [31]. This could enable the controller to easily determine whether aircraft at the same altitude were on conflicting paths. The coloring could also make it easier to ignore distracting stimuli on the control display (i.e., to filter out aircraft at other altitudes).

Once an information source is attended to, the cognitive processes of detection and recognition come into play. These processes make up human perception. Human perceptual activity has been characterized in detail by signal detection theory (SDT) [34]. In any task environment there is the probability that a stimulus may not be detected by an operator due to its discriminibility from distracters (or noise). At first thought, this seems a simple problem to address—increase the intensity of the signal to make it detectable. However, engineering psychology research has demonstrated that detection is influenced not only, for example, by whether a digital display feature is bright enough or an auditory warning loud enough to account for human sensory capabilities [35], but it is also dependent on the payoffs and penalties associated with operator success or failure in detection, as well as signal expectancy. In other words, mental model–referenced cognitive processes affect detection. These issues, along with the amount of sensory stimulation, serve to influence an operator's sensitivity to a signal.

The types of errors that can occur in a detection task, which are modeled by SDT, include *false alarms* and *misses.* The former involves operators indicating perception of a signal in a task environment when none exists. A miss involves overlooking an actual signal. *Hits* and *correct rejections,* which constitute detection of an actual signal and no false alarm in the absence of a signal, respectively, characterize operator success in SDT.

Human sensitivity to environmental stimuli is dictated by an operator's *response criterion,* or the level of sensory stimulation associated with a signal in the presence of noise compared to noise alone. This response criterion is adjusted on the basis of the probability of a signal occurring. For example, Drury and Addison [36] demonstrated that sheet-metal inspectors predictably adjusted their response criteria for detecting defective parts based on historical defect rates. Similar results have been obtained in the study of service task domains, including lab technician screening of medical patient x-rays for the presence of tumors [15] based on the historical prevalence of cancerous tissue. The implications of operator response criterion shifts on the design of human-machine systems are presented in Table 6.7.2, along with design methodologies to address signal detection task performance needs.

TABLE 6.7.2 Signal Detection Task Performance Needs and Design Methods Addressing Operator Response Criterion Shifts

Performance need	Design methodology
• Ensure operator expectations match actual signal probabilities.	• Use task training. • Provide operators with information on expected signal rates.
• Exaggerate operator sensitivity to task critical stimuli (e.g., defective parts in an assembly process).	• Introduce decoys or false targets into the task environment to heighten operator awareness. • Instruct operators in costs associated with missing targets or approving defectives. • Instruct operators in relationship between target detection and monetary rewards or penalties for missing defects.
• Adjust operator response criterion for task.	• Provide memory aids on targets (e.g., defect states). • Provide near-real-time feedback on operator performance.

Pitfalls in the signal detection process (as part of human information processing) exist, including vigilance decrements. Operators of complex systems, designed through the traditional, technology-centered design process, are often relegated to the role of monitor (detecting critical system events) as a result of the majority of system functions being assigned to automation. Human monitors of automation are highly susceptible to boredom, complacency (a lack of suspicion of system behavior), and distracting attentions. These psychological states and noise can lead to decreases in detection performance over time, with decrements having been observed within 30 minutes of task initiation [37]. Vigilance decrements occur due to (1) loss of operator sensitivity motivated by a reduction in signal intensity compared to noise, (2) operator response criterion shifts due to potential uncertainty about where stimuli will appear in the task environment, and (3) operator failure to recall signal characteristics due to infrequency of occurrence and fatigue [15].

Vigilance decrements and their underlying causes can be addressed through human-machine system design that promotes signal detection. One design solution to vigilance decrements involves enhancing stimuli through redundant cues in interfaces. For example, auditory warnings in aircraft cockpits have been used by commercial airline manufacturers as redundant cues (in addition to warning lights) to secure pilot selective attention under high-workload conditions. The use of redundant information coding in the cockpit has also been studied by the U.S. Air Force, revealing that in dense visual displays, pilots are better able to determine the degree of threat when information is presented using both shape and color, compared to the use of either dimension alone [38]. These redundancies in coding warnings serve to reduce visual search tasks and uncertainty about the location of a specific warning. Consequently, operator response time may be reduced.

An additional interface design consideration relevant to signal detection in human interaction with complex systems (potentially serving to reduce vigilance decrements) is proximity compatibility theory (PCT). This theory states that information sources conceptually related to one another or used in an integrated manner should be perceptually grouped [31]. (It is related to the design recommendation of reducing distances between information sources related in an operator's mental model of a system, focusing on organization of information displays [39] for optimal perceptual performance.) According to PCT, displays may be grouped on the basis of similar characteristics [40] or the need to perform parallel processing of information [41]. Wickens and Carswell [41] have intimated that grouping of displays may produce emergent features that otherwise would not be apparent to operators in a poorly organized display. Woods et al. [42] designed visual displays for nuclear power plant control panels in which information on six to eight different process variables was integrated into a single display producing unique graphical shapes depending on the state of the system. These PCT-based emergent feature displays facilitated efficient and effective error condition identification by eliminating the need for the operator to sample multiple independent displays and integrate mental information.

Transition. Human functions in complex systems control for which the cognitive processes of attention and perception are most relevant include systems monitoring and processing plan implementation. Monitoring has been discussed as a function that humans commonly maintain in acting as supervisory controllers to intelligent automation. Unfortunately, it is a role to which they are generally ill suited [43]. System design considerations aimed at addressing operator signal detection in monitoring and vigilance tasks have been discussed. Human attention allocation and signal detection in implementing processing strategies for controlling an automated system are important because the perception of information facilitates higher cognitive processes, including the probability that SA will drive decision making and, ultimately, action execution. The following section focuses on these processes and their relation to human-machine system design.

Situation Awareness and Decision Making

Situation awareness has been defined by Endsley [44] as "the perception of the elements in the environment within a volume of time and space, the comprehension of their meaning, and projection of their status in the near future." For example, a pilot must be able to attend to and perceive a multitude of stimuli from cockpit displays as well as environmental information beyond the cockpit. To develop SA, the pilot relates perceived information to task objectives and overall goals, which facilitates determination of the relative importance of each piece of information. Subsequently, projections are made on the basis of task-relevant stimuli to determine appropriate courses of future action. This process is not unique to aircraft piloting, but is pervasive across task domains in which humans interact with complex systems, including medical systems and process control [45,46].

Factors influencing SA can be categorized as system, task, or operator variables. Table 6.7.3 lists those variables that Endsley [29] has identified as being associated with the development of SA. Of these factors, SA appears to be critically limited by memory stores, particularly short-term memory (STM) capacity [47]. Working memory, or STM, serves as the cognitive mechanism for integration of perceived information, whereas long-term memory stores are more concerned with historical states of a system. As well, STM allows for integration of new information with operator mental models, morphing operator conceptualizations of how a system may behave given specific environmental inputs [48]. Working memory is critical to comprehending the current state of a system and predicting future behavior given changing environmental circumstances [31]. Through STM, SA plays a critical role in human mental model development for interaction with complex systems. Unfortunately, human working memory capacity and retention has been shown to be severely limited. Miller [49] stated that humans are limited in STM capacity to 7 ± 2 chunks or logical groups of information. The duration of working memory has been shown to be limited to about 20 seconds [50]. Young [51] provided empirical evidence of the STM capacity of air traffic controllers that supports Miller's "magical number." He found that only highly experienced controllers were able to keep a mental record of approximately 10 aircraft at the same time, with information on each aircraft being chunked (e.g., altitude, heading, airspeed).

Situation awareness is important to human-machine system design because it has been associated with operator dynamic decision-making ability [52,53]. This ability can have a significant impact on overall system performance. Decisions made under high task demands and time stress rely heavily on an operator's ability to perform situation recognition and recall of potentially appropriate scripts or sequences of control actions for maintaining system performance. For example, a nuclear power plant controller must be able to recognize patterns of operational circumstances (e.g., high core coolant exit flow temperature, high core containment pressure, and high radiation containment security) through pattern-matching current

TABLE 6.7.3 Influential Factors in Situation Awareness by Category

System	Task	Operator
• Complexity	• Environment	• Stress
• Autonomy	• Overall design	• Workload
• Interface design	• Complexity	• Memory stores
• Feedback	• Duration	• Innate abilities
• Required training	• Required experience	• Automaticity in task performance

displays with long-term episodic memories. This recognition drives recall of control actions—for example, to increase coolant flow (given the state of the system)—and, ultimately, the decision to do so.

Additionally, SA is important to systems design because it serves to explain human goal-driven or top-down processing. Unlike early conceptualizations of human information processing (including perception, working memory and decision making [30]) that characterize the human as a passive sponge, absorbing information from the environment and developing task goals on that basis, SA conceptualizes humans as active information seekers searching for environmental stimuli to support goals and objectives [29] developed through internal processes involving long-term memory, working memory, and active, dynamic decision making.

Situation-Awareness Errors. In order to identify methods by which human-machine system design can reflect considerations of operator SA for enhancing performance, it is necessary to discuss errors that may occur in the development of SA and, consequently, mental model formulation and decision making. Situation-awareness errors can occur in human perception, comprehension, or projection of environmental information. Endsley [29] has defined three levels of SA—Level 1, Level 2, and Level 3 SA—which correspond to these cognitive processes. Level 1 SA errors include failing to perceive goal-related information. In simple terms, the operator ends up missing a piece of the puzzle. For example, if a pilot is subjected to high stress and workload levels, perception may be inhibited due to attentional narrowing, causing a Level 1 SA error. In this situation, task workload is so great that the pilot develops "cognitive tunnel vision" and focuses only on stimuli that have previously proved to be accurate and reliable in decision making, ignoring all other information due to a lack of cognitive resources. Level 1 SA errors may also occur due to the STM limitation discussed previously. Insufficient working memory may not permit system state recognition through integration of stimuli with long-term memory (LTM).

Level 2 SA errors involve failure to relate Level 1 SA to task goals. Influential factors include a lack of operator expertise and LTM stores to recognize a particular chunk of task information as being important to processing. For example, if a pilot fails to relate flap configuration to the different stages of flight (e.g., takeoff, en route, and landing), the performance of the aircraft may be seriously compromised. This was the case for the Northwest Airlines MD-80, which crashed on takeoff at Detroit Airport due to improper configuration of flap and slats [5]. Another type of Level 2 error dependent upon expertise as well as environmental cues is operator selection of the wrong mental model from LTM. Consequently, operator expectations of system results are not in line with actual behavior. This can result in severe consequences to overall performance.

Level 3 SA errors may be caused when a person's mental model of a system is not well developed enough to allow for prediction of future system states. This could be due to lack of operator training in a broad set of operational circumstances that allow accurate projections of system states based on new environmental information. For example, in the context of advanced manufacturing systems, operator mental models of traditional machining operations using lathes and milling machines may not be appropriate for electrodischarge machining. Specifically, knowledge of input parameter settings, including speeds and feeds, may not transfer to electrical current settings affecting metal removal rates or surface finish. Other Level 3 errors may result from operator inconsistency in the selection of action scripts based on situation recognition or trouble in distributing attentional resources across cognitive processes and maintaining goals.

Situation Awareness in Human-Centered Systems Design. Methods by which to improve system design to reduce SA errors and improve overall performance are presented in Table 6.7.4. The table also presents benefits associated with specific methods and considerations necessary to their application.

The design of automated control in human-machine systems should be carefully considered for its impact on SA. The information processing pitfalls of vigilance decrements and complacency due to relegating humans to the role of systems monitor are relevant to SA as well. If the perceptual process is inhibited, operators may develop inaccurate Level 1 SA, which is the building block for the higher levels (i.e., comprehension and projection). The degree of autonomy in human-machine systems and errors in higher cognitive processes, including SA, caused by operator out-of-the-loop performance will be discussed in detail later.

Decision Making and Performance

As previously mentioned, decision making plays a critical role in systems performance. Like SA, it is severely limited by the small amount of information we can store and manage in working memory. Both the speed and accuracy of decision making are limited by STM capacity and retention [15]. These limitations are reflected in, for example, human ability to estimate mean system parameter values, probabilities of occurrence of critical system events (errors), and reliable functioning of system components, as well as the ability to project future system states (based on SA) of current task judgments. Other influences in decision making include heuristics and biases, or rules of thumb and tendencies based on experience. They have developed

TABLE 6.7.4 Recommendations for Improving Operator SA and Potential Benefits

Recommendations	Benefits	Important considerations
• Limit information displays to goal relevant information. • Format information to support development of accurate SA.	• Improved effectiveness in operator perception. • Improved maintenance of task objectives and overall goals.	• Consider task features and individual factors influencing attention. • Relate operator information requirements to interface features.
• Design system interfaces with information displays organized according to operator's goals. • Do not organize displays based on similar features alone.	• Improved task performance • Reduced visual travel between displays. • Reduced visual search times. • Improved maintenance of task objectives and overall goals.	• Consider limitations of human STM. • Consider operator ability to distribute attentional resources. • Consider operator ability to tolerate high levels of stress and task workload.
• Present task information critical to triggering accurate situation classification.	• Improved operator selection of appropriate action scripts. • Improved system performance. • Preventing operator selection of incorrect mental models for action.	• Identify critical cues necessary to develop SA. • Consider SA in training program design. • Educate operators in what information to look for, when to look for it, and where.

because of human information processing limitations such as those related to STM. They account for the limited capacity of working memory to objectively and efficiently evaluate all possible alternatives in a dynamic situation, as would be prescribed by multiattribute utility theory [54]. The brain develops heuristics and biases as shortcuts in decision making to permit timely action. However, this usually compromises decision accuracy or leads to illogical decisions [15]. Biases specifically cause us to be influenced by (1) the order in which information is presented [55], (2) the frequency of presentation, and (3) whether new information matches previous information (i.e., how the decision is framed). Specific biases include the following:

1. *Conservatism.* Humans tend not to revise their initial hypotheses on a situation as much as they should (see Waganaar and Sagaria [56] for an example related to predictions).
2. *Anchoring.* Operators tend to assign greater importance to information displayed early in task performance compared to more recent information [57].
3. *Confirmation.* Humans will seek environmental stimuli confirming their hypotheses and will ignore contradictory information (e.g., Sheridan [58]).

Heuristics include the following:

1. *Representativeness.* Humans primarily rely on pattern matching for decision making and assign little consideration to the likelihood of an event occurring in a particular context.
2. *Availability.* Humans assign greater importance to information more easily brought to mind (attended to in STM) [59].
3. *As-if scenario.* Humans will treat all sources of information as if they are equally likely and reliable [57].

With respect to the representativeness heuristic, Fischoff and Bar-Hillel [60] state that humans are influenced more by salient features and visible attributes of a task than by internal concepts of event probabilities.

The potential implication of inaccurate decision making due to heuristics and biases on human-machine system performance dictates the need to design system interfaces that limit irrational operator behavior. Design methods by which this can be accomplished are listed in Table 6.7.5 along with justifications for their use.

Transition. System design considerations of higher cognitive processes, including comprehension and projection for decision making, should be based on human and technological function analysis. The human factors design implications associated with various aspects of cognition relevant to system functions to be maintained by a human operator must be taken into account to ensure the effectiveness of complex, dynamic systems. Additionally, human factors guidelines on control configuration based on physical ergonomics should be considered in the design process. To a large degree, useful control design is related to physical ergonomics—human coordination and tactical limitations. However, cognitive ergonomic issues, including signal-response compatibility and population stereotypes, have been demonstrated to be critical factors as well. For the purposes of space and brevity, human behavioral issues in control design are not included here. For a thorough review of both topics, refer to Wickens [15].

AUTOMATION AND THE OUT-OF-THE-LOOP PROBLEM

In function allocation, as part of the human-centered system design process, the question arises regarding how much automation should be applied. This is a very important question because the answer dictates the role of the human operator in the control loop. Human-centered automation should be considered for application with the objectives of reducing human errors in performance and moderating operator workload.

TABLE 6.7.5 General Interface Design Methods to Improve Human Decision Making

Recommendation	Importance of application
• Eliminate conflicting information sources from displays.	• Contradictory stimuli lead to operator confusion. • Conflicting information sources cause reliance on confirmation bias.
• Present system information globally.	• Information presented in stages encourages operator use of anchoring bias. • Operators may tend to focus on earliest information presented.
• Provide operators with sufficient time and information to make decisions.	• Limitations of STM cause operator reliance on heuristics and biases under time stress. • Limitations of STM often do not permit operators to store any and all information related to decision.
• Design decision-making training protocols.	• Operators need instruction in waiting for information to make accurate decisions (see Fig. 6.7.2). • Task time stress may cause operators to rely on availability heuristic. • Lack of training in probability of occurrence of events encourages operator conservatism.

Wickens [15] offers two reasons for implementing automation in human-machine systems. Automation can achieve error reduction by (1) performing functions humans do poorly and (2) assisting in areas where humans have limitations. Other reasons exist, such as those used by the commercial airline industry to cut labor costs by reducing crew size. This justification for automation has also been used in many manufacturing industries, which have introduced advanced technologies into the workplace that require limited human supervisory control. All of these reasons must be considered carefully in light of human-automation interaction issues. For example, how effectively can a human pilot communicate with an automated flight engineer compared to a human flight engineer? Problems can occur by improperly gauging the degree of automation required for error prevention or workload moderation. A system can be automated beyond what is needed, reducing human capabilities and removing the operator from the control loop completely. (This is especially the case in automating for crew size or workforce reductions.)

The Out-of-the-Loop Performance Problem

Endsley and Kiris [61] used the terminology *out-of-the-loop (OOTL) performance problem* to refer to a set of negative consequences associated with reducing the role of the human operator in complex systems control through technology-centered automation. It specifically refers to the problem of reducing human interaction with complex systems to the point where operator response times to critical events are slowed, particularly system errors and failures, and a loss of SA occurs.

Negative consequences of the OOTL performance problem include operator complacency [62] and vigilance decrements [63], which lead to a loss of SA [61], and operator skill atrophy [64] over the long term. These consequences may result from an increased monitoring role for operators in conjunction with the development and implementation of automation to address cognitive activities historically maintained by the human, including task planning and decision making, yet not the role of systems monitoring. This makes sense, as providing artificial intelligence with sensory capabilities approaching those of human beings has been a daunting and unattainable task for computer scientists. Unfortunately, as discussed previously, monitoring is a function that humans are not well suited for due to task distracters and susceptibility to boredom. Consequences of OOTL performance may also result from increased system complexity as a result of automation. Wickens [15] suggests that automation usually increases the transparency of the system or the level of detail of a system that is displayed to an operator. As well, the number of subsystems that must be monitored by an operator may increase beyond human capabilities. In this scenario, operators tend to simply give up and ignore task responsibilities that they cannot maintain. Consequently, the probability of system errors and failures may increase because high monitoring loads lead to missed signals.

A critical consequence of OOTL performance is monitoring-induced complacency, or a lack of operator suspicion of system behavior. In interacting with highly reliable systems, such as commercial aircraft and nuclear power reactors, operators often exhibit overtrust in automated controllers and become complacent, failing to enter the control loop to correct system errors when needed. Pilot overtrust in advanced-technology aircraft can be detrimental to overall system performance because of the compounding factor of autopilot capability to camouflage errors or malfunctions. For example, engine failures can be accounted for automatically by autopilot control of flight surfaces. Conversely, improper flap and slat configuration can be handled automatically through changes in engine thrust. If pilots fail to periodically intervene in the control loop to assess systems, they may not be capable of correcting erroneous situations that arise from autopilot failure. A lack of SA may prohibit pilot understanding of system problems and what needs to be done to correct errors. Parasuraman et al. [62] studied the effect of automation-induced complacency in human monitoring of fuel systems in a simulated flight task battery that included tracking and resource management tasks. They found that monitoring performance was significantly affected by changes in system error rates and by the success rate of an automated controller in detecting errors. That is, depending on the overall reliability of the system and automated control, changes in operator complacency were apparent.

Unfortunately, complacent behavior often leads to operator vigilance decrements or failures to detect system information. This lack of perception can degrade operator Level 1 SA. Vigilance decrements and a loss of SA may be caused not only by factors internal to the human operator, but also, for example, from a lack of system feedback. Highly automated systems are often designed such that humans function as supervisory controllers, overseeing normal operations and deciding whether to intervene in the control loop to correct potential automation errors. To function in this capacity, operator cognitive load must be reduced by eliminating distracting information, such as data on the inner workings of the system [15]. This, however, may also serve to reduce operator SA and inhibit accurate mental model development.

As part of supervisory control (see Sheridan [65] for definition), human decision making regarding system performance (under normal operating conditions) is passive; that is, the operator does not exercise direct control over the system, but rather he or she decides whether manual control may be necessary. Endsley and Kiris [61] found OOTL performance and passive decision making to be associated with reduced operator system awareness. Conversely, operator active involvement in control-loop decisions affecting systems performance was associated with heightened states of awareness.

Although not trivial, OOTL performance leading to a loss of SA may be a less serious issue for human operators than skill atrophy. If human operators are removed from the control loop of a machine system over extended periods of time, their manual skills and general knowledge of how to operate the system may substantially degrade to the point of not being able to maintain functions assigned to them. For example, pilots flying transatlantic and transpacific flights in advanced-technology aircraft may be afforded the opportunity to rely on autopilot control for durations of five hours or more. Over the course of many flights, their absence from the aircraft control loop may cause forgetfulness of appropriate courses of action when they are required to fly manually. Shiff [64] conducted a study in which human subjects were trained (via simulation) to control a paper production facility under different control modes, including manual, supervisory, and complete automation. Persons subjected to repeated manual training proved to be more efficient and effective in the manual mode than persons who had been trained in manual control followed by supervisory control.

The OOTL performance problem is an important issue in gauging the degree of automation in human-machine systems, because losses in operator SA and manual control skills have been found to be critical to human ability to react to, and recover systems from, failure modes [26,61]. In efforts to reduce operator workload and prevent human errors under normal system functioning, failure mode performance may necessarily be compromised through system automation. Thus, the OOTL performance problem may serve as one potential vehicle by which to determine the appropriate level of automation based on operator ability to deal with system errors and failures.

Human-Centered Level of Automation

In order to determine the optimal degree of automation in human-machine systems, current literature offers approaches to design that consider the need for operator workload reduction along with prevention of the negative consequences associated with OOTL performance. Essentially, this is a double-edged sword, as workload reduction is supportive of increased automation, and limiting human OOTL performance (monitoring) is supportive of reduced automation and greater active control. For example, Wickens [15] offers an approach to system design incorporating flexible automation that allows for different arrangements of human and automated control. He suggests that automation could be turned on or off depending on operator workload levels. Or varying degrees of automation could be implemented to allow for operator control loop involvement beyond monitoring; at the same time, workload could be moderated. Workload reductions might occur by using automation for routine and mundane system functions while allocating to human operators higher-level cognitive functions that they are good at performing, such as planning and decision making. The following discussion offers two general approaches to human-centered automation design that consider workload and OOTL performance issues.

General Approaches. Based on technological analysis within the system design process and on human factors research, the capabilities of available automation and human operators can be determined. This information can answer the traditional design question as part of function allocation: What can be automated? Unfortunately, it does not serve to answer the following question: What should be automated in light of the human issues in human-automation interaction, including loss of SA? Human factors research has sought to address this question by defining static and flexible automation arrangements that optimize system performance under normal operating conditions and failure modes. Further, definitions have been developed based on underlying factors in losses of SA, including complacency and vigilance decrements due to high-level automation.

Two approaches have been developed to define not only the “what” of automation, but the “when” and “how”: *human-centered level of automation* (or control) (LOA) and *adaptive automation* (AA), sometimes referred to as *dynamic function allocation.* Figure 6.7.3 graphically presents the problem space to be mapped by defining human-machine system automation according to these methods. It equates LOA to how much automation should be applied and AA to when it should be applied.

Defining levels of automation (LOAs) involves allocating fixed functions to human and computer servers with the objective of maintaining both in the control loop, thus preventing operator OOTL performance problems while deriving the benefits of automated processing. Human-centered LOA is appropriate for systems in which the function allocation strategy does not change over time or in systems capable of dynamic automation for which it is useful to identify discrete function assignments across humans and computers. Studies have devised different levels of autonomy (control assignments), such as supervisory control [65], blended decision making [26], decision support [66], and shared control [28], which involve complete computer responsibility for all active decision making and human monitoring, joint human-computer planning and decision making, human decision making based on computer plan-

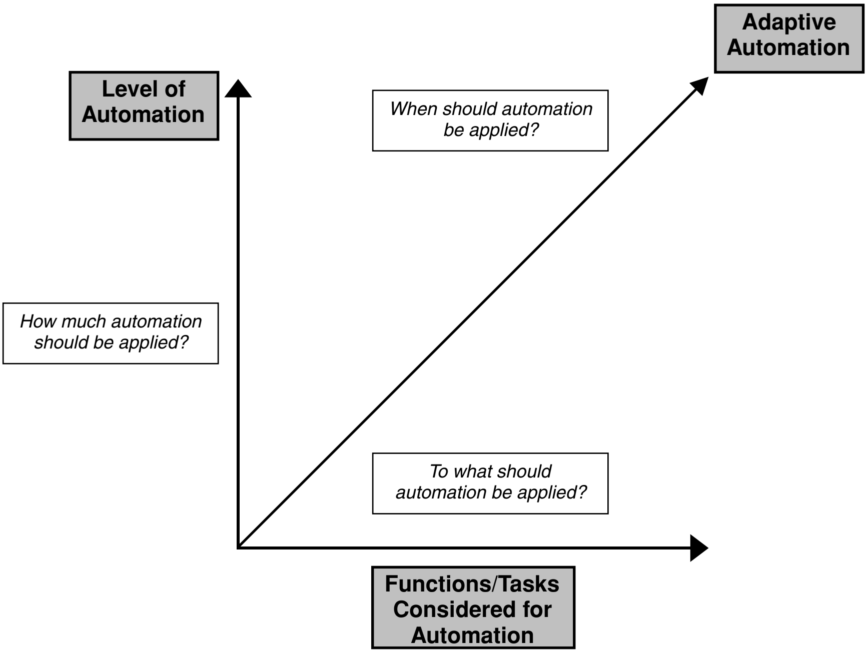
Adaptive Automation
Level of Automation
When should automation be applied?
How much automation should be applied?
To what should automation be applied?
Functions/Tasks Considered for Automation

FIGURE 6.7.3 Automation design considerations (adapted from Endsley, 1997).

ning, and joint human-computer task implementation, respectively. These levels can be considered intermediary settings on a continuum of control from human manual functioning to full automation. They have been presented with other intermediate LOAs in taxonomies attempting to provide meaningful rankings of levels. For example, Sheridan and Verplanck [27] developed a list of LOAs for joint human and computer decision making in the context of undersea teleoperations (see Table 6.7.6).

The levels in the list range from complete human control to full automation and prescribe distribution of different functions, including "gets", "selects", "starts", "requests", "approves", and "tells", to either server in controlling a teleoperator. Sheridan and Verplank's [27] taxonomy is one of the most descriptive taxonomies found in the literature in terms of identifying

TABLE 6.7.6 Sheridan and Verplanck's [27] Taxonomy of LOA

Description of Level of Automation
1. Human does the whole job up to the point of turning it over to the computer to implement.
2. Computer helps human by determining the options.
3. Computer helps determine options and suggests one, which human need not follow.
4. Computer selects action and human may or may not do it.
5. Computer selects action and implements it if human approves.
6. Computer selects action, informs human in plenty of time to stop it.
7. Computer does whole job and necessarily tells human what it did.
8. Computer does whole job and tells human what it did only if human explicitly asks.
9. Computer does whole job and decides what the human should be told.
10. Computer does the whole job if it decides it should be done; if so, tells human if it decides the human should be told.

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what the human and computer are to do under the different LOAs and how they work together. However, none of the levels presented in this list has been empirically assessed to determine its influence on teleoperator performance or human operator SA (in relation to failure mode performance) and thus to differentiate one level from any other as being more appropriate.

Endsley and Kaber [26] developed an LOA taxonomy of 10 levels based on assignment of functions to a human operator and an automated system, including monitoring, options generation, selection, and implementation (see Table 6.7.7). This taxonomy has been empirically assessed in the context of a dynamic control task regarding the effectiveness of the various means of facilitating intermediate LOAs to ameliorate OOTL performance problems. Results have demonstrated overall system functioning and operator SA (under both normal operating conditions and failure modes) to be significantly impacted by the functions assigned to the human and/or computer under each LOA. Levels of automation involving human decision making accompanied by computer processing have produced superior performance, even when compared to fully automated functioning. Further, levels requiring blended human and computer decision making or computer selection with human review have yielded improvements in SA (Endsley and Kaber, [26]). These findings suggest that retaining both humans and computers in the active system control loop to perform certain functions may be effective for preventing OOTL performance problems associated with a loss of SA and for enhancing system performance.

Dynamic Function Allocation

As an alternative method for defining automation with the objective of optimizing overall system performance (under normal operating conditions as well as failures), flexible function allocation involves allocating some functions to a human controller and some to a computer, while others may pass back and forth between the two servers. Control of functions that either server can perform may be allocated adaptively across time, depending on different human, task, and environmental factors. For example, as discussed previously, monitoring tasks usually promotes boredom in human operators and, over time, can be fatiguing. These cognitive implications can lead to performance degradations. If human-machine system automation is adaptive, it can be switched on and off to deal with human monitoring performance decreases, or the LOA may be shifted among intermediary levels, from a high level (e.g., supervisory control) to a low level (e.g., manual control), to further involve the operator in the control loop.

Another strategy toward establishing an appropriate schedule of automation over time, based on performance, involves study of both operator and machine functioning. Parasuraman [67] proposed a behavior-modeling approach in which control allocations between

TABLE 6.7.7 Endsley and Kaber's [26] Taxonomy of LOA

	Functions			
Level of automation	Monitoring	Generating	Selecting	Implementing
1. Manual control	Human	Human	Human	Human
2. Action support	Human/computer	Human	Human	Human/computer
3. Batch processing	Human/computer	Human	Human	Computer
4. Shared control	Human/computer	Human/computer	Human	Human/computer
5. Decision support	Human/computer	Human/computer	Human	Computer
6. Blended decision making	Human/computer	Human/computer	Human/computer	Computer
7. Rigid system	Human/computer	Computer	Human	Computer
8. Automated decision making	Human/computer	Human/computer	Computer	Computer
9. Supervisory control	Human/computer	Computer	Computer	Computer
10. Full automation	Computer	Computer	Computer	Computer

human and computer servers are used to attain a predetermined pattern of overall performance. In this approach, task variables are also considered, such as whether an operator has completed a system task or is in the process of implementation.

Factors other than operator performance can serve as useful indicators of when automation should or shouldn't be applied to system control to abate human OOTL performance consequences. Monitoring human operator workload through physiological measurements, such as electroencephalogram signals [68] or heart rate variability [69], and secondary task measurements [70] has been studied for its usefulness in predicting control allocations to maintain human involvement in active control and to moderate cognitive workload.

Beyond monitoring operator performance and workload to determine the need for dynamic function allocations, monitoring system events has also been advocated as a mechanism to AA. Morrison and Gluckman [71] proposed an approach to AA involving monitoring for system errors and/or failures to determine the need for human operator intervention in control loops to perform system recovery.

All of the preceding approaches to dynamic function allocation have the objective of taking advantage of the capabilities of automation while maintaining a necessary level of human involvement in system control during normal operations to ensure operator preparedness for potential system failures. Adaptive automation, applied according to different strategies, has been investigated in laboratory settings to determine its effectiveness in obtaining this objective. For example, Parasuraman [67] used an aircraft piloting task battery to study the performance-based approach to AA. He found that human performance in a systems monitoring (failure-detection) subtask was improved by periodic allocations of manual control to operators, compared to static automation (i.e., no manual control allocations). Hillburn et al. [72] used the same task battery to study the performance measurement approach to AA. They found that human functioning in a tracking subtask was significantly better with AA than with purely manual tracking. They also found the same to be true for the monitoring subtask that Parasuraman [67] studied.

The results of these studies suggest that AA may provide performance benefits to human operators who monitor systems and perform tracking tasks. These benefits result from maintaining human operator involvement in active control and suggest the need for assessing the usefulness of AA for application to cognitive tasks as well.

Summary. The human operator has been retained in automated system control loops to deal with disturbances (i.e., unanticipated system states) such as automation failures. The question to be answered by human factors engineering is, how can human-machine systems be optimally configured for automation on the basis of human and technological issues to capitalize on the benefits of automated processing while keeping the human adequately prepared to deal with anomalous operational conditions? Human-centered levels of autonomy and AA appear to be promising approaches to the symbiosis of human and machine in both static and dynamically configurable complex systems.

BENEFITS

Human factors engineering is useful only in so far as it contributes to the safety and efficiency of engineered systems. From a systems perspective, it can contribute to performance by promoting desirable system states and by helping to avoid undesirable states. In real terms, it contributes to performance by optimizing the contribution of human operators during mission completion and by helping them avoid human error. It may also reduce the overall cost of system operation by helping to avoid harm to users, other persons, or the environment in which the system is embedded. Therefore, it can perform in both a system-enhancement role and a hygienic role. The latter is often the strongest motivator for inclusion of human factors engineering in system design.

Of course, it is critical that the benefits of human factors engineering be justifiable in terms of investments in engineering labor, equipment, operator training, and so forth. Cost-benefits analysis for human factors has been explored by Rouse and Boff [73], among others. They list the products of human factors as solutions, tools, methods, guidance (e.g., principles and standards), information, advice, and influence. These products carry with them potential benefits, principally the following: (1) provision of solutions not possible without human factors; (2) performance made possible by or enhanced by human factors; (3) enhanced user perception of value; and (4) cost avoidance, including avoidance of mishaps.

They point out that these benefits do not always carry a clear economic value. The value of performance enhancements may be easy to measure as a productivity gain on a shop floor, but is less amenable to quantification in, for example, a military setting. Cost avoidance may be easy to measure as reduced wastage, but difficult to quantify in terms of avoiding, for example, traffic accidents.

Simpson and Mason [74] outline how the economic benefits of human factors may be assessed in industrial settings. They point out that ergonomic intervention is traditionally justified based on health and safety (i.e., as an industrial hygiene issue). However, they propose that economic justification may provide an even more powerful motivator for management. They contend that data for estimating cost improvements stemming from human engineering may be found in several areas. Personnel records can provide data for assigning costs to absenteeism, turnover, training, and compensation (including the results of on-the-job injuries). Safety records can identify accident "black spots," requirements for special precautions, and requirements for special safety equipment. Medical records can be used to determine the frequency, nature, and length of absence related to injuries or health problems. Work studies can identify relaxation allowances in personnel compensation and costs associated with individual variability in job performance, reject rates, and inspection costs. Plant engineering data can be used to assign costs to downtime, maintenance costs, and wastage. These areas are all potentially sensitive to human engineering, for example, in job design, workstation design, machine system design, or training. Simpson and Mason believe that these data, combined with either life-cycle cost accounting or estimation of productivity enhancements, can be used to make a case for good return on investment for human engineering.

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CHAPTER 6.8

THE BIOMECHANICAL PROFILE OF REPETITIVE MANUAL WORK ROUTINES

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The causes of cumulative trauma disorders are complex in their nature and usually no single factor or simple reason can be found to explain them. Cumulative trauma disorders or repetitive strain injuries have developed into a major source of occupational disability, and their causes and contributory events need to be carefully analyzed. A methodology for resolving the biomechanical cause of a trauma due to job requirements is proposed in this chapter. The method relates to the potentially hazardous movements that appear in a frequent manner during selected work cycles. The chapter presents an inspection and analysis approach to be performed on jobs involving manual effort, aiming to enhance safety and trauma prevention. The methodology is demonstrated in an industrial application where the analysis of a highly manipulative task is performed.

REPETITIVE MOVEMENTS IN MANUAL WORK

The impact of job-related illnesses on a substantial portion of the workforce due to cases of cumulative trauma disorders has become a health trauma as well as a productivity issue. The professional literature is constantly reporting on how production rates and worker satisfaction have dropped because of occupational related illnesses—especially in the upper body and hands. Among the most affected industries are automobile manufacturing, newspaper publishing, and meatpacking. The necessity of understanding the physiological causes of occupational injuries is growing, since more safety issues and ergonomics intervention programs are imposed by work regulations. The trends in disabilities associated with cumulative trauma disorders (CTD), repetitive motion injuries (RMI), repetitive strain injuries (RSI), and related occupational disorders have been steadily advancing during the present decade. The cost of such job-related illnesses of the upper extremities due to loss of time on the job, retraining personnel, compensation claims, and medical treatments is considerable. The incidence of claims is rising and both the public and private sectors are working to curtail the trend. The need to understand the way external physical events overload body structures is now, more than ever, expressed by both industrial engineers and ergonomists.

Repetitive Manual Jobs

During the execution of common operations in industrial, service, and clerical jobs, the worker performs a collection of repetitive activities, many of which are repeated in a cyclic manner. Cyclic tasks are usually performed with the muscles of the hands, arms, and shoulders, assisted by the eyes; and will therefore require head and neck movements. A common repetitive job will usually demand low energy consumption, but when such a job is frequent in its appearance, short in duration, and cyclic in performance, the recovery phases of the musculoskeletal organs are limited and therefore strenuous. It has been concluded from experience that limited recovery time between consecutive motion repetitions is highly demanding physically, and will very often be associated with symptoms of inflammations and muscular soreness. Joint and ligament inflammation, muscle soreness, and tendinitis and tenosynovitis, as well as different kinds of bursitis, are occupationally grouped under the term CTD. These symptoms are related to muscle tenderness and overuse, nerve entrapment, and arthritis problems. Academicians and practitioners across the board have agreed that constant research should be conducted to single out and clearly describe the components of activities that may lead to CTD.

The causes of CTD are complex in nature and usually no single factor can be identified. When ergonomic approaches are utilized to reduce such occupational disorders, a variety of human and workplace-oriented factors can be listed. The main objective in studies dealing with occupational trauma and repetitive disorders is the evaluation of the bodies involved in the task; which usually will be directed by the aftereffect [1]. Monitoring worker performance is often done to determine the contributing hazards that caused the disorders in the worker body. Recordings of body movements and body positions have been performed for many years. These started with choreography recordings; later the military and space sciences became interested in the study of postural configurations; and in the last decade they have been documented in work situations. From a research point of view, especially regarding safety issues, there is a need to analyze job requirements to resolve the potential hazard in routine tasks.

Several task analysis methods have been introduced in recent years to document job activities and to serve as a postural evaluation procedure [2]. Most of the methods involve traditional work measurement systems, which in many situations are very detailed and also time consuming. Traditional work measurement systems, although they are solid quantitative techniques to obtain data on human performance, are limited in their ability to provide the inputs necessary to deal with ergonomical aspects of repetitive tasks. Industrial engineering systems, when used in the traditional industrial way, have been found to be difficult to explain to ergonomists and medical and insurance practitioners, who are non-engineers [3].

Research is still far from complete on exactly what causes CTD. Researchers, so far, have failed largely because of differences in the way studies are designed and how cases are diagnosed. Therefore an attempt has been initiated to develop a systematic approach, which uses motion performance measurements along with biomechanical schemes, to enhance the ability of non-engineers to predict occupational hazards in manual tasks. In practice a worker, in order to satisfy job demands, performs various body movements, mostly by the hands, which operate in a cyclic manner on repetitive tasks. Repetitive work routines, when not safely conducted, are expected to affect musculoskeletal components of the individual worker. These routines should be improved and changed. Manual maneuvers required by a given job can be seen as a series of tasks that makes up the job activity. These tasks are composed of a discrete set of skilled iterated production steps that are typical to the specific job, and take place sequentially within the work routine. Each routine can accordingly be divided into cyclic segments that are repeated in the task time frame, as will be further explained.

AN ERGONOMIC METHODOLOGY

The need for a methodology that features possible ergonomic improvements is being expressed more now than ever before. Today, most of ergonomics and industrial safety studies define occupational risk factors in tasks after a trauma has been accumulated. Unlike traditional practice, the paper is directed to ergonomic inspection and up-priory determination of hazardous movements, with a special emphasis to monitor performance of short-cycle and frequent manual events.

The proposed technique employs guidelines for job screening of manual routines, aimed to characterize the hazardous motion elements in the given job. The potential of a manual act to accumulate the risk and become an occupational disorder is determined through a detailed analysis of its kinesiology, called the motion's *biomechanical profile.* For this purpose, the content of job demands and work routines are reviewed, and repetitive work elements are identified for further time-and-motion study and in-depth biomechanical investigation. The analysis is based on frequencies and performance time of the selected motion acts. The biomechanical profile is a quantitative description of each motion element, relevant exclusively to the way a task is performed. It is believed that a set of biomechanical profiles, related to a joint segment, when presented in a simple manner, provides the practical knowledge about how the human joints execute a task.

Breakdown of a Job

A job breakdown and motion element classification procedure enables the user to concentrate on the evaluation of a relatively small and significant number of motions. According to a set of guiding rules, only highly repetitive motions, static postures, and motion elements—where force is applied in repetitive patterns—are considered for in-depth investigation. The methodology is different from present techniques, because of the attention given to repetitive, static, and forceful work elements, since these, more than other occupational stresses, have a direct impact on the musculoskeletal and neural systems. The proposed procedure relates itself to manipulative tasks and therefore focuses on the upper body, with special emphasis on the flexion, extension, deviation, and twisting movements of hand, wrist, upper arm, and neck.

A breakdown of a given job into subactivities is presented in Fig. 6.8.1. According to this scheme, a job can be seen as a set of tasks and motion elements that are repetitive

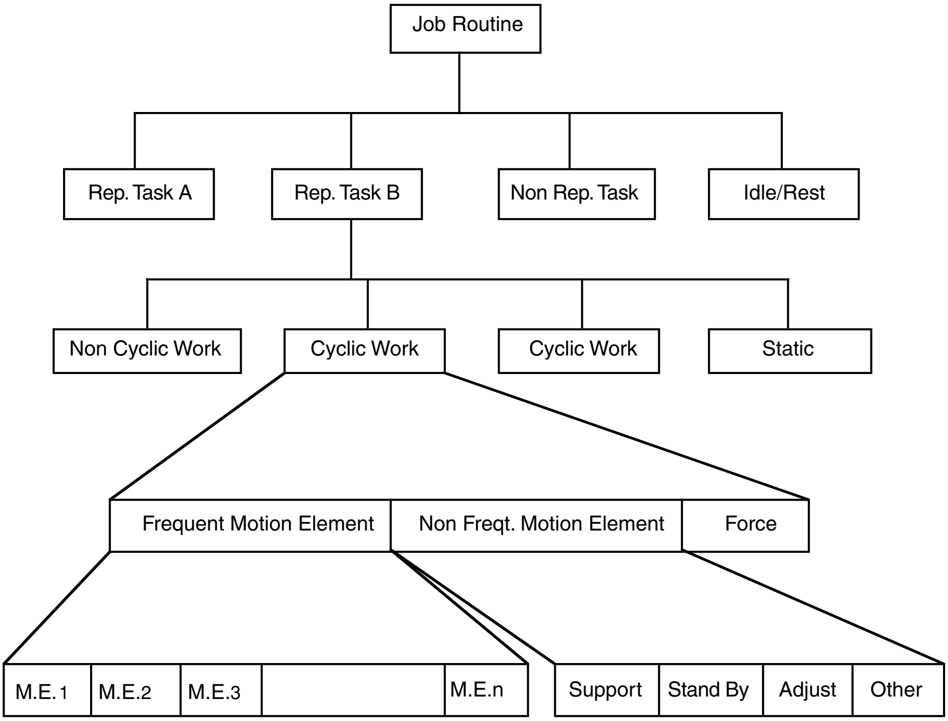


FIGURE 6.8.1 Breakdown of a job into its subactivities.

and nonrepetitive. The nonrepeated tasks, as well as resting or idle periods, are excluded from further consideration, since they do not present inherent potential hazards. Repeated tasks are then further observed for determination of their cyclical appearance and the level of stress they impose. Manual tasks are very often performed under dynamic and static efforts which, when accumulating, generate muscular fatigue and acute pain.

There is no sharp line between dynamic and static effort, but since static effort is much more arduous than dynamic, the static component of mixed effort assumes the greater importance. Static effort will appear when the body is providing hold, support, lifting, or pulling-pushing movements for long periods. During static effort the flow of blood is constricted in proportion to the force exerted. If the effort is 60 percent of the maximum, the flow is almost completely interrupted. It has been found that when the force effort is less than 15 to 20 percent, the tension in the muscles is less and blood flow should be normal.

Static muscular effort, where blood supply to organs is obstructed, can be a stressful factor when it occurs in a repetitive manner, and may accumulate to become a trauma. According to Grandjean [4], static effort can be considerable under the following circumstances: If a high level of effort is maintained for 10 seconds or more, if moderate effort persists for 60 seconds or more, or if slight effort is about one-third of maximum force and lasts four minutes or more, muscular fatigue from static effort will increase in proportion to the force exerted. This can be expressed in terms of the relationship between the maximal duration of a muscular contraction and the force expended. According to Monod [5], static force that exerts 50 percent of maximum force can last no more than 60 seconds. Field studies show that 15 to 20 percent of the maximum force will induce painful fatigue if such effort has to be kept in repetitive appearance [6]. From the author's experience, 20 seconds of moderate effort is a preferred limit for manual static effort. Occupational efforts derived from static effort should therefore be considered for in-depth analysis.

Work cycles are usually composed of short, frequent motion elements, and nonfrequent and forceful motion elements. When applying force is needed to execute a job demand, the frequency between the forceful acts becomes a major influence in the development of injury. If recovery time between two consecutive forceful acts is less than twice the motion duration, it is considered as a strenuous physiological effort that may lead to CTD. A nonrepetitive motion can be any adjust or hold motion by one hand, while the other hand is performing a manipulative move. Forceful motions in this case are being further analyzed if they appear in a frequent manner.

As experienced by the author in many industrial cases, a frequency rate of more than six forceful moderate movements per minute should be considered for analysis in the case of CTD prevention acts. Support, stand by, adjust, and other work-related motion elements have been noticed many times in micromotion analysis. The motions that do not involve strenuous physiological demands are not considered for further analysis. The basic segment of a cyclic job is the motion element; it is usually performed by a local muscle group, and carries a definite motion-time value. Such motion elements can be referred to as *Gilbrethian motion elements,* according to Predetermined Motion Time Systems, such as MTM's basic motions, or carry specific professional definitions given by the evaluator. The cyclic motion elements and the movements involved in the work cycle are grouped into a sample, which will be analyzed. The way a worker performs these frequent strenuous motions will be studied and related to occupational functions, leading to physiological reactions, which may lead to trauma.

The cyclic work and the motions to be investigated, usually in a micromotion study, have to be carefully decided since a slow-motion review is a time-consuming process. A time value of 30 seconds is considered an upper limit for tasks with a fast working pace. In the practice of motion and time study, 10- to 30-second cycles have been found to be common in repetitive manual work.

EVALUATION OF REPETITIVE MOTION ELEMENTS

In-depth analysis of motion patterns by using traditional industrial engineering techniques, such as motion and time study, is difficult to perform and very time-consuming. It is, therefore, recommended to concentrate on potentially hazardous elements that have been determined to be real contributors to trauma. On the basis of this reasoning, the following limitations for motion selection are recommended:

- Duration of the work cycle 30 seconds or less
- Static effort if maintained for 20 seconds or more
- Force effort when applied six times per minute or more

To obtain a detailed objective description of the job demands because of the occurrence of repetitive motion elements, the use of a video camera is recommended, to view all aspects of working routines and record the upper body in motion. A preferred recording setup will provide two to three sagittal views of the left and right hands and a view of the coronal plane, which requires the use of three cameras. Reflective markers are to be located on the joints of the hands, arms, and upper torso; they should be noted on the monitor to help observe rotation and planner movements. The views from the cameras can be projected in split frames on a computer screen or a multiple monitor setup. The recorded videos are to be studied in slow motion or in a frame-by-frame evaluation process.

Screening Repetitive Manual Work Elements

The major variables to be established are the motion time values and the percentages of the most dominant elements in the work cycle, and the frequencies of the basic motion elements. An algorithm for screening repetitive manual elements that might be hazardous or associated with CTD is presented in Fig. 6.8.2. The procedure considers a few steps to be followed; these steps are presented in a decision flow format. The first step is to determine manual job demands from a single worker. On this basis one can break down the job into work routines. The evaluator then selects the repetitive routines and defines the work cycles, where the exertion of hand movements is required. Work cycles are to be defined according to the theory of motion-time study [7]. A routine is considered repetitive when repeated in the range of 20 to 30 times per working hour. The next step is to select the repetitive motions in the cyclic routine, considering factors as duration of motion (<30 seconds), static effort (>20 seconds) and force exertions (>6 per minute).

The given decision diagram represents a preferable algorithm to aid in the selection process. After the major work cycles have been selected, the main motion elements that make up the work cycle have to be identified. The next step is to determine the motion time and frequencies of the selected motions. The frequencies of these motion elements are to be counted from the videos. We then refer the motion elements to the body joints involved in the hand maneuvers. Angular intervals for each of the joints will be defined and set within the range of the specific joint. The biomechanical profile of performance will be related to the selected body joints and motion elements, as will be demonstrated in the following case study. The way movements are performed is presented by their motion patterns; this can be described on the basis of angular deviation for a given motion element. The next step is therefore to determine directions of the motion from the start to end points, and to configure the motion pattern as performed in one typical motion cycle. The final step is the determination and presentation of the biomechanical profiles for each of the body joints, as performed by the set of motion elements for the selected work cycle.

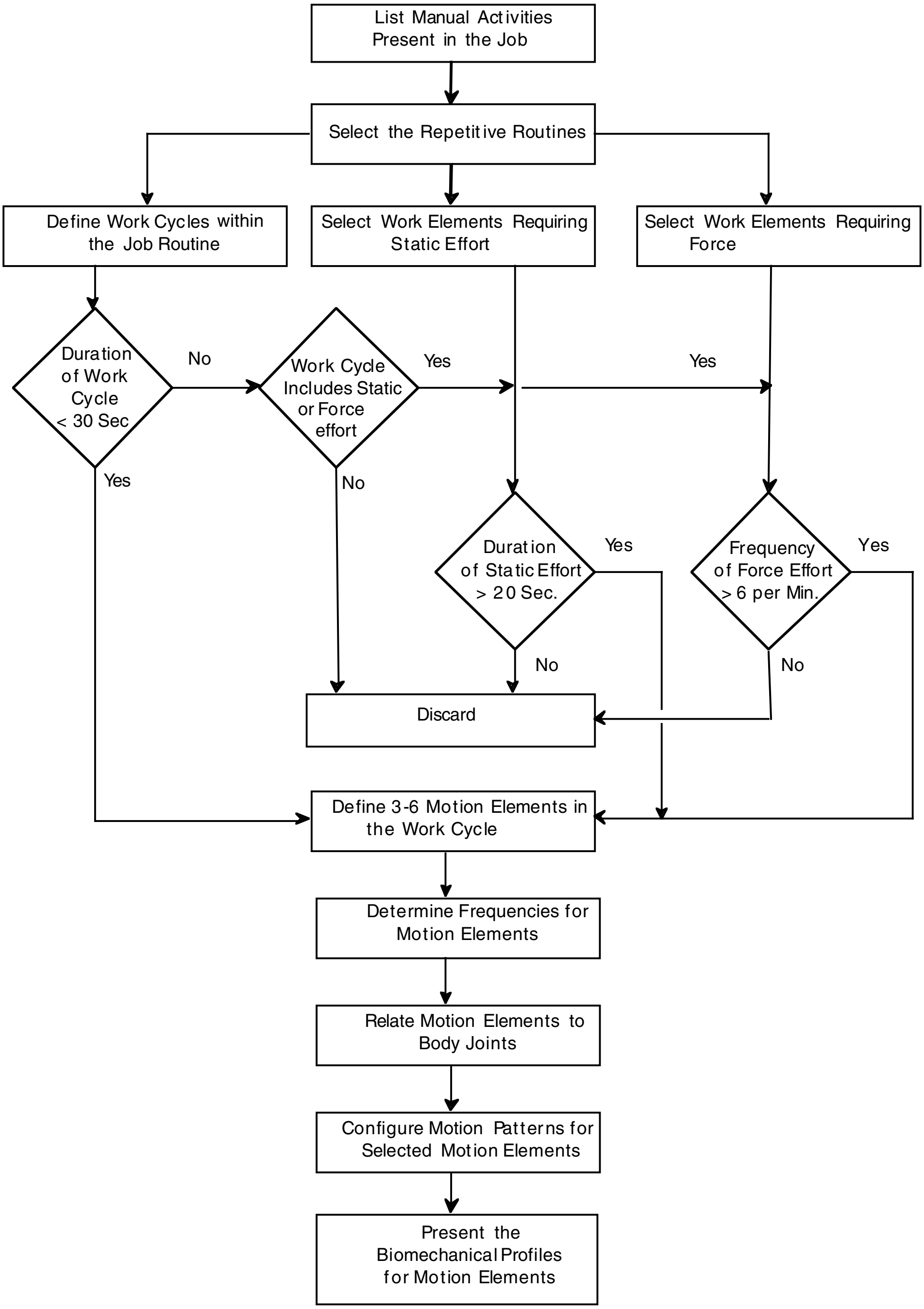

List Manual Activities Present in the Job
Select the Repetitive Routines
Define Work Cycles within the Job Routine
Select Work Elements Requiring Static Effort
Select Work Elements Requiring Force
Duration of Work Cycle < 30 Sec
No
Yes
Work Cycle Includes Static or Force effort
Yes
No
Yes
Duration of Static Effort > 20 Sec.
Yes
No
Frequency of Force Effort > 6 per Min.
Yes
No
Discard
Define 3-6 Motion Elements in the Work Cycle
Determine Frequencies for Motion Elements
Relate Motion Elements to Body Joints
Configure Motion Patterns for Selected Motion Elements
Present the Biomechanical Profiles for Motion Elements

FIGURE 6.8.2 Algorithm for screening hazardous work elements.

THE BIOMECHANICAL PROFILE OF REPETITIVE MANUAL WORK ROUTINES

The following body joints are of interest in repetitive manual performance activities: wrist, elbow, shoulder, and neck. When large objects are handled, or long hand reaches are experienced, the upper back should be studied as well, and a thoracic joint should be added. Angular deviations of each of these joints (particularly when recorded in 3-D) can describe the exact postural kinesiology during each phase of a repetitive manual activity. The biomechanical profile, as will be seen later in Fig. 6.8.5, is a set of planar graphs describing the motion frequencies for the angular deviation and a specific joint action. It has been found that such a projection serves as a good predictor for repetitive motion disorder analysis. The combined effect of the angular deviation and motion frequencies as seen in the graphical presentation has been very useful in the determination of potentially hazardous movements.

AN INDUSTRIAL APPLICATION

The described methodology has been performed in a few industrial situations where highly manipulative task procedures lead to CTD, as in the manufacturing of diamonds. The study of repetitive motion patterns in the diamond industry aimed to investigate occupational hazards to the upper extremities involved in the polishing processes. The polishing processes employ 86 percent of the work force in the sorted diamond industry. The findings of a survey, conducted on 246 diamond workers pointed out that 40 percent of the polishers reported pain in their upper limbs—compared to 3 percent among the general population. In this study group, 64 percent reported pain in the shoulders, 36 percent complained of pain in the upper arms, and 27 percent cited pain in the hands. These complaints were in addition to ulnar nerve damage observed in workers in the diamond industry.

Industrial Case Study

The diamond polishing process is based on grinding a fixed rough diamond on a horizontal turning polishing disk surface that has been coated with diamond powder. By correctly positioning the rough diamond against the high-speed turning disc, the friction forces created by millions of small sharp edges of carbon-hard particles are able to grind the rough surface to a mirror-smooth surface. Because of its natural hardness, only grinding by friction against similar hard carbon edges is effective in shaping the diamond to its geometric and brilliant finish. Due to the molecular structure of the diamond's carbon layers, the grinding forces will be effective only if the polishing act is directed against the natural grain of the diamonds' rough surface.

Figure 6.8.3 presents a schematic description of a diamond polishing workstation, in which the major components are outlined. To address the safety issue and detect the occupational hazards, an ergonomic study was designed. The purpose of the study was to analyze the repetitive motions and relate motion frequencies in defined working routines to potential physiological disorders. It was predicted that the findings from the motion analysis would lead to a biomechanical discussion of occupational safety issues. A detailed motion time study was conducted on skilled workers to unveil the relationships between the diversified procedures in the manufacturing of diamonds [8].

Diamond-Polishing Procedures

The polisher's tasks were carefully examined through a micromotion study, using 3-D video recordings of a wide collection of manual movements involved in the polishing routines. The study included all of the different polishing activities and body motions demanded by the complex performances required in this job. A wide selection of diamond products differing in

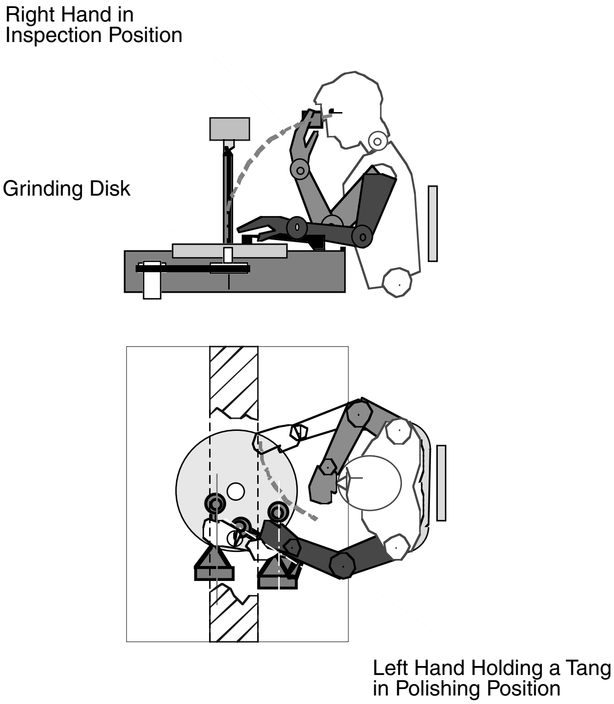


FIGURE 6.8.3 A diamond-polishing workstation.

size, shape, and geometry status of the rough stone was studied. After analyzing various cyclic routines, it was possible to divide the manual activities into two basic routines, which differ by duration, complexion, and level of repetitiveness: a short routine, referred to as the *polish cycle,* and a long routine, referred to as the *facet cycle.* These two routines represent the highly manipulative tasks involved in the completion of one diamond product, and served as the work cycles to be further analyzed.

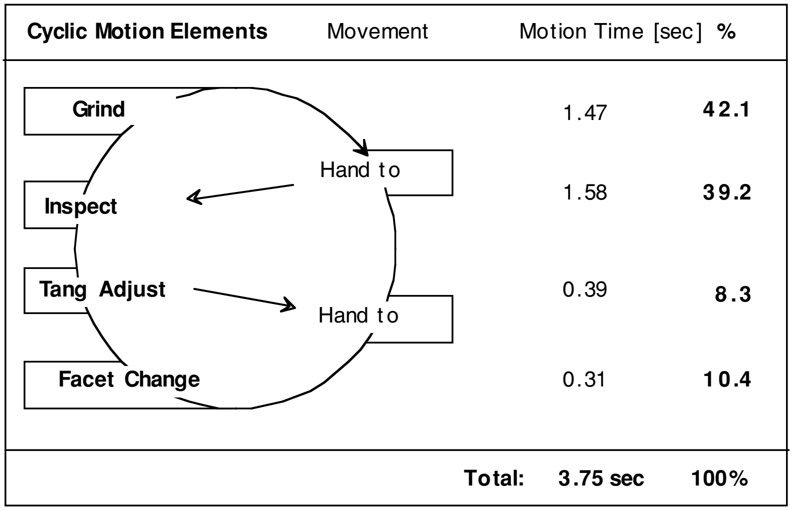
The process of selecting a limited but highly repetitive sample of motions made the ergonomic evaluation much simpler and more focused on a few "target motions." Because of the complexity of the manual activities, as performed by the skilled diamond worker [9], a typical motion-time study would have required an extensive amount of time and an expensive professional effort in order to measure all of the motions involved in the process. Instead, the screening procedure provided a good filtering algorithm that helped to focus on those motions that are highly repetitive and therefore more CTD hazardous.

The diamond facet, one of 57 found in a polished brilliant stone, which is the basic geometrical property of any diamond, served as a good reference regarding the polisher's performance. In order to obtain representative values, the worker's performance was recorded at different times during the day, for normal, everyday processes, over a variety of diamond rough surfaces. Posture and body movements were evaluated during recordings of actual working postures in industrial setups. A tabular form was developed for the study with all observed variables integrated into it, enabling the analysis of each working element. The form of data recording consists of the body joints on the horizontal line and the motion elements on the vertical line; motion frequencies were recorded in the joint-motion intersections. Using the suggested method [10], the study has provided the reasons for the repetitive disorders in diamond polishing, which later guided ergonomic improvements in the manufacturing of diamonds.

Four basic hand movements make up the polishing process: *grinding, inspection, tang adjustment,* and *change of facet.* The *tang* is a rigid handle that holds the rough diamond during the polishing activity. It was observed that 94 percent of the operators performed the polishing activity in a similar manner. By analyzing videos for hundreds of tasks, recorded with the clock running in real time, the evaluation team was able to measure time duration and motions needed to perform each of the four basic motion elements. These motion elements are short in duration and very rapidly performed.

The Biomechanical Profile

Figure 6.8.4 shows the four motions involved in the polishing cycle, and the two major movements connecting the basic motions in the cycle. The times for *adjust* and *change* are very short, while the *inspect* and *grind* motions require more than 80 percent of the cycle time. The videos were studied once again in order to establish the positions of the worker's wrists, hands, and arms in relation to the work elements. The frequencies of the movements for the basic motion elements of the five body members involved in the polishing activity were recorded. A segmented biomechanical analysis of the motion patterns followed by the body members was made. Angular rotations were detected: shoulder: flexion/extension, internal/external rotation and adduction/abduction; elbow: flexion/extension and pronation/supination; wrist: planar flexion/extension and ulnar/radial deviation; neck: flexion/extension; and back: flexion/extension.



Cyclic Motion Elements	Movement	Motion Time [sec]	%
Grind		1.47	**42.1**
Inspect	Hand to	1.58	**39.2**
Tang Adjust	Hand to	0.39	**8.3**
Facet Change		0.31	**10.4**
	Total:	**3.75 sec**	**100%**

FIGURE 6.8.4 Cyclic work routine as experienced in the diamond polishing industry.

The biomechanical profile of a body member consists, in the case of the polish cycle, of four motion elements on the vertical axis, together with the frequency of motions performed at each stage, and angular deviation of the motion on the horizontal axis. The graph presented in Fig. 6.8.5 provides simultaneous information of the left hand and right hand motions in relation to the angular position of the joint. The graphical projection of an angular deviation for a

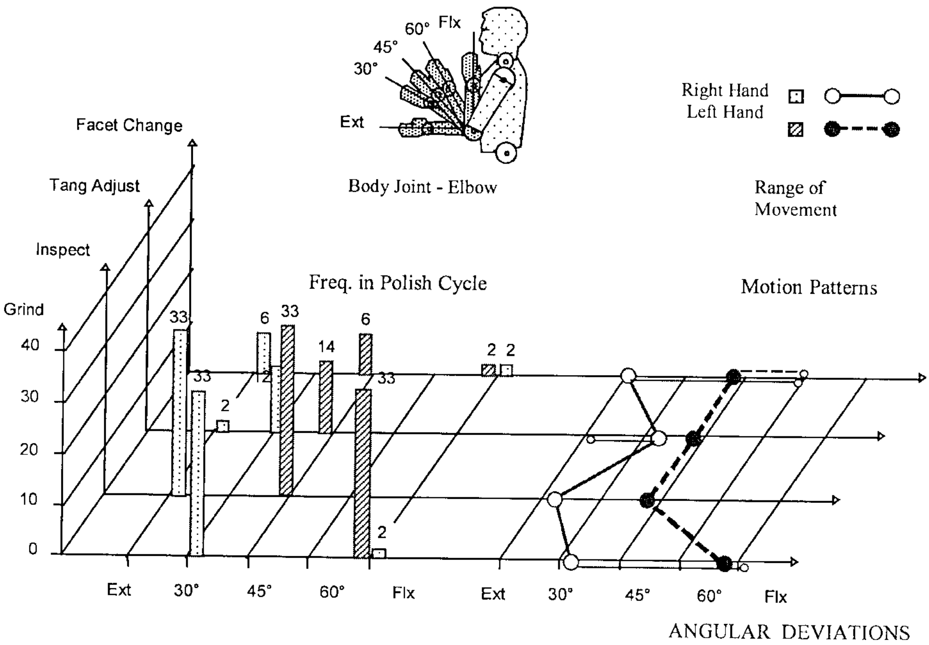


FIGURE 6.8.5 The biomechanical profile of the elbow in flexion/extension movements.

movement, as related to a body member, is a presentation of the kinesiology of joint's main movements in the activity. Figure 6.8.5 also shows the biomechanical profile of the elbow joint in the facet cycle. This process includes the repetitions of the polishing cycle.

It can be seen from the scheme that 35 repetitive *grind* motions by the right hand and 33 by the left hand have been observed during the cycle. Most of the right hand motions (33) are in the 30-degree flexion interval; 2 right hand motions are in full flexion. All left hand (33) *grind* motions are in full flexion. Fewer repetitions are performed in the *tang adjust* motion element: 12 right hand repetitions are in the 30-degree angle and 2 in extension; for the left hand all 14 are in the 45-degree flexion angle. Very few repetitions were observed in the *facet change* motion elements, which were scattered within the angular range. When analyzing motion patterns, one can see that the right hand is moving along the entire angular range of the elbow joint, between full flexion and full extension. The left hand is more positioned and is moving between the 45-degree angle and flexion.

A biomechanical analysis of motion patterns as obtained in the diamond study indicates that most of the actual movements of both hands are performed by elbow flexion/extension, by forearm pronation/supination, and by wrist ulnar/radial deviation. During the grinding activity in the polishing cycle, both shoulders are abducted in an angular range of between 45 and 60-degrees. During inspecting, adjusting, and facet changing, the shoulders are abducted in the angular range of 30 to 45-degrees. The shoulder function was in "locked" form to stabilize the arm; this is best accomplished in a neutral position where the muscles involved are shortened and exert maximal strength. The presentation of the polishing motion pattern had not only explained the cause of trauma but also aided in the effort that would lead to a solution. Based on the biomechanical understanding of the manual activities, and the motion patterns involved, one can redesign the processes. The motion pattern scheme provides a good reference for safe activity intervals in relation to the cyclic

THE BIOMECHANICAL PROFILE OF REPETITIVE MANUAL WORK ROUTINES

motion elements, for example, the redesign of the workstation, so that the right elbow will act within a more limited angular joint interval. Redesigning repetitive tasks to prevent future CTD has been found to be the most permanent and cost-effective solution to the problem of cumulative trauma.

CONCLUSION

The causes of cumulative trauma disorders are complex in nature and usually no single factor or simple reason can be identified during the job evaluation. Cumulative trauma disorders and repetitive strain injuries have developed into a major source of occupational disability; their causes and contributory events need to be carefully studied. The necessity for understanding physiological causes of occupational injuries is growing at this time, when more safety issues and ergonomics intervention programs are imposed by work regulations. This was the rationale for the proposed methodology aiming to resolve the biomechanical cause of the potential trauma. The method relates to the hazardous movements that appear in the most frequent and selected work cycles. The methodology has been demonstrated in an industrial application. It can be used in the analysis of jobs with a large portion of manual effort.

Differences between the number of movement repetitions at the shoulder level and elbow or wrist level have been observed in these profiles, indicating that the shoulder muscles are more involved in the pushing forces during the polishing activity. The increased pushing movements are clearly observed in the micromotion analysis when force exertion on the polishing tool, held by the left hand, were noticed. It has been observed as well that when high grinding forces are required, the right shoulder will always assist in pushing the tang (the polishing handle) to the grinding disc.

The Graphical Presentation

A combined graphical presentation of about four biomechanical profile motion elements clearly explains the biomechanics of the repetitive motions involved, which enables the understanding of the physiological behavior. While observing the motion frequencies, on the left side of the diagram of the biomechanical profile (Fig. 6.8.5)—the bar diagram—one can see that the motion frequencies by themselves do not provide enough information about the movements involved in a repetitive activity. The right part of the diagram shows the cyclic motion patterns. These will contribute to the understanding of the applied kinesiology by outlining the *motion tracks* during the manual action. When task improvements are considered, this kind of motion presentation may serve as a design tool. By defining the "safe borderlines" for minimum and maximum extension or rotation movements, one can determine the guidelines for improvements of a given manual activity. The designer can then simulate hand and arm activities to be performed along the safe lines.

This case study concentrates on the study of the most frequent motions. When work measurement is performed, instead of using a PMTS or Therblig's motion elements, motions are referred to as vocational descriptions of the work elements. This eases the reference of terms and is better understood by nonprofessionals and workers. Occupational hazards are related to body members, which will simplify the diagnostic procedure and direct ergonomic improvements to safe kinesiology and to the sources of the cause of the problem. The risk factors can be identified before trauma occurs, and provide a biomechanical scheme of the selected motion elements. Further use of motion patterns can set safety limits in ergonomic designs, by defining more universal rules for safe angular deviations.

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BIOGRAPHY

Issachar Gilad is a member of the Industrial Engineering and Management faculty at the Technion-Israel Institute of Technology. He holds B.Sc. and M.Sc. degrees in industrial engineering and management and a Ph.D. in ergonomics and biomechanics. His professional activities are in the fields of industrial engineering, ergonomics, and biomechanics. He is involved in academic and industrial projects such as ergonomics design of man-machine systems, productivity studies in manufacturing and service operations, and design for the disabled. He is the author of about 100 articles in professional journals and reviews and has participated in about 50 international and local conferences. Professor Gilad has served as a consultant to industry and governmental agencies since 1980. He serves on numerous scientific editorial boards in the area of industrial engineering and ergonomics. Professor Gilad served as chairman of the Israel Ergonomics Society (IES) during 1994–1998; he is currently president of the IES.

CHAPTER 6.9

INTERNATIONAL ENVIRONMENTAL STANDARDS BASED ON ISO 14000

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Riding the wave of enthusiasm from the quality management system standard (ISO 9000 series), many are calling for the same type of revolution in the environmental and occupational safety and health worlds with emerging standards such as the ISO 14000 series. While apparently more skeptics than proponents exist, it remains to be seen whether ISO 14000 and other environmental management system standards will experience similar growth and become a part of corporate culture. Even though logic would suggest that a systematic method of handling an organization's impact on the environment would be an effective approach, many see ISO 14000 as yet another consulting scam or paperwork jungle. ISO 14000, however, is much less stringent than its 9000 counterpart, with many systematic requirements but few documentation requirements. Occupational safety and health, a related area, will not see its own ISO standard any time soon, but the environmental management system standards (ISO 14000) are flexible and allow the inclusion of safety and health into the overall system. ISO 14001 defines *environment* as the "surroundings in which an organization operates, including air, water, land, natural resources, flora, fauna, *humans,* and their interrelation."

This chapter will provide an overview of ISO 14000, with a particular focus on ISO 14001, the specification standard for environmental management systems. Further discussion will be given on implementation of environmental management systems, both on a general and detailed level. Finally, the chapter will discuss several case studies of implementations of ISO 14000. This emerging set of standards could have a tremendous impact on the industrial engineer(s) of an organization. If an organization decides to implement this type of system into its operation, virtually everyone in the organization will be affected. Additionally, industrial engineers are typically tasked with improvement projects and often are asked to take on responsibilities in the environmental and occupational safety and health areas.

OVERVIEW

There has been a great deal of interest in management system standards from the International Organization for Standardization (ISO) in Geneva, Switzerland. The latest entry to the world of international standards is the ISO 14000 series on environmental management, which introduced five standards in their final form late in 1996. ISO 14000 is a set of voluntary environmental management system standards that provides the framework for identifying, controlling, and improving an organization's impact on the environment. These standards are not regulations, but simply provide an example of how to structure a management system geared toward improving the environment. ISO 14000 actually comprises a series of standards with associated numbering schemes. For example, ISO 14001 is the specification standard that outlines the required elements of an effective environmental management system. The reasons for implementing ISO 14000 into a particular organization will be discussed later.

While interest in the ISO 14000 standards is quite high, many organizations are waiting for more motivation to actually implement these environmental management systems and obtain registration to them. By mid-2000, between 30 to 40 organizations in the United States had achieved registration to the specification standard ISO 14001 [1]. This chapter will discuss the area of international environmental and occupational safety and health management and some of the issues regarding implementation of these systems. Additionally, several case studies will be presented to give the reader an understanding of how some organizations have made the commitment to these management systems and implemented them, if not registered to them. Finally, conclusions and speculations on the future of ISO 14000 will be discussed in the summary.

ISO represents the International Organization for Standardization. The letters *I-S-O* are not meant to be an abbreviation but are used because the prefix *iso* means equal, and standardization is a big part of what ISO is all about. It would be difficult to list in this chapter all the accomplishments that ISO has achieved, even before ISO 9000. For example, credit card thickness is universal, in great part due to the efforts of ISO. The emergence of ISO 9000 and ISO 14000 has made this organization more well known.

Before discussing ISO 9000, some general clarifications about management system standards should be made. First, these management standards are voluntary standards, not government-enforced regulations. Presently, an organization in the United States does not have to implement an ISO management standard to comply with environmental law. However, it may be required to conform with one of these standards to do business with a certain customer or in a certain country. Second, these standards are not prescriptive in nature. For example, ISO 9000 does not give specific tolerance levels or otherwise dictate the level of quality a certain product must achieve but simply provides a framework for a quality management system within an organization. Likewise, ISO 14000 does not give specific effluent levels or other environmental performance level requirements. While the lack of specific environmental performance requirements in ISO 14001 has been criticized, many believe that implementation of an effective management system can't help but improve on the end-of-pipe environmental performance. Finally, registration to one of these standards is not directly with ISO, but with another party. Second-party registration is obtained with a customer or other party with a vested interest in the organization. Third-party registration is obtained with a registrar that is accredited by another organization—jointly by American National Standards Institute (ANSI) and Registrar Accreditation Board (RAB) in the case of ISO 14001. ISO 14001 even allows an organization to self-declare conformance to the standard, although some outside stakeholders may consider this less credible than second- or third-party registration.

As of December 1996, approximately 255,000 organizations worldwide had obtained registration for one of the standards in the ISO 9000 series [2]. Of these, approximately 15,475 were from North America and 11,738 were in the United States [3]. One of the reasons for the great interest in ISO 9000 is that many organizations are required by their customers to become registered to one of the ISO 9000 standards as a prerequisite to doing business. This is quite apparent in certain industry sectors, such as the automotive industry. Additionally, the pressure to remain competitive in the marketplace has forced many companies to obtain registration.

Compare the number 11,738 to approximately 30 to 40 companies that have obtained registration to the environmental management system standards and it is easy to see that ISO 14000 has a long way to go to catch up to its quality counterpart. Many believe that ISO 14000 will grow to a level similar to ISO 9000 but that remains to be seen. One final issue regarding these two sets of standards is integration. An organization that wants to implement a seamless management system that covers all areas, including quality and environmental, may see barriers because there are two different standards. This is why the two technical committees (TCs) that were assigned to write and maintain the standards (TC 207 for environmental and TC 176 for quality) have been tasked to work together to ensure that the standards are compatible. An environmental management system (EMS) is recommended for a number of reasons. The primary reason for establishing an EMS at a facility is to provide a systematic approach to proactively addressing environmental issues. Many facilities simply react to problems such as the receipt of a notice of violation (NOV) from a regulatory agency. Since one of the requirements of an EMS based on ISO 14001 is periodic compliance evaluation of a facility, a proactive approach to managing environmental issues is established. A second requirement of an EMS is a commitment to prevention of pollution. A facility that actively pursues this concept will eliminate an environmental problem before it occurs. A third requirement of an EMS is a commitment to continual improvement. If this concept is incorporated in an integrated management system, a facility will not only remain compliant with the regulations but improve profitability through an increase in productivity.

The authors have conducted several hundred environmental, health, and safety (EH&S) audits at industrial facilities. It is our experience that industrial engineers are often selected as EH&S managers. There are a number of reasons for this selection. First, these individuals have a general engineering education that does not usually provide expertise in a specific manufacturing process. These individuals have had to learn the specifics of the processes at their facility. Likewise, there is no training school for EH&S compliance. This experience must be learned on the job. The flexibility of industrial engineers makes them excellent candidates for EH&S managers.

ISO 14000 INTRODUCTION

The technical committee that has developed and continues to work on the ISO 14000 standards, TC 207, was formed in 1991 by the secretariat of ISO at the recommendation of the Strategic Advisory Group on the Environment, or SAGE. SAGE studied the need for international standards on environmental management systems and believed there were compelling reasons for their development. The areas of activity for TC 207 are listed, with corresponding numbers for standards that have been developed to date:

- Environmental management systems (ISO 14001/14004)
- Environmental auditing (ISO 14010/14011/14012)
- Environmental labeling
- Environmental performance evaluation (ISO 14031)
- Life cycle assessment (ISO 14041)
- Vocabulary (ISO 14050)
- Environmental aspects in product standards

The first standards to emerge in final form were two in environmental management systems and three in environmental auditing. Another area that is emerging is life cycle assessment, which has recently produced a sixth final international standard. ISO 14001—Environmental Management Systems (EMS), Specification with Guidance for Use is the only standard for which organizations will be able to obtain registration. The other standards are written as guidelines to help in various parts of the EMS. Copies of these standards can be obtained from a variety of sources, including ANSI, American Society for Testing and Materials (ASTM), and American Society for Quality Control (ASQC). Most of the remaining areas of

ISO 14000 are in earlier stages of development with the standards being in committee draft or working draft form. Table 6.9.1 gives a full, detailed account of the standards included in ISO 14000 by number [4], description, and their status as of summer 1998.

The reasons for implementing an environmental management system have not been fully answered. Some of the compelling reasons that led to the explosion of ISO 9000 are just not present with ISO 14000 at this time. Regardless, there are many good reasons to implement an environmental management system such as ISO 14000. These include

- Improving the company's public image regarding the environment
- Improving environmental compliance and/or performance through the implementation of a formal system
- Gaining a competitive advantage or a perceived advantage
- Providing evidence of "good faith," which may reduce or possibly eliminate penalties in the event of noncompliance
- Meeting customer expectations or demands by implementing an EMS
- Improving processes overall through formal continual improvement program

There are some potential disadvantages to implementing ISO 14000. The biggest may be cost, although many organizations are finding it easy to obtain quick paybacks on the initial investment. ISO 14000 implementation involves changing the way an organization does business, and change rarely comes without a price tag. Additionally, there are direct costs associated with obtaining an ISO 14001 registration, such as the costs for a registrar to conduct the audits. Again, it is up to each organization to determine whether the costs outweigh the benefits and whether registration is the ultimate goal. Many are finding it beneficial to implement an environmental management system now but wait for additional incentives before applying for registration.

TABLE 6.9.1 ISO 14000 Standards Description

Number	Document description	Document status*
ISO 14001	Environmental mgt systems—specification	Final standard as of 9/1/96
ISO 14004	Environmental mgt systems—guideline	Final standard as of 9/1/96
ISO 14010	Auditing—general principles	Final standard as of 10/1/96
ISO 14011	Auditing—audit procedures	Final standard as of 10/1/96
ISO 14012	Auditing—auditor criteria	Final standard as of 10/1/96
ISO 14015	Environmental aspects of sites and entities	Committee draft early 1999
ISO 14020	Labeling—general principles	Publish late 1998
ISO 14021	Labeling—self-declaration—terms	Publish late 1998
ISO 14024	Labeling—guiding principles & procedures	Publish early 1999
ISO 14025	Type III labeling	On hold
ISO 14031	Evaluation of environmental performance	Publish mid 1999
ISO 14032	Case studies illustrating use of 14031	Publish mid 1999
ISO 14040	Life cycle assessment—principles	Final standard as of June 1997
ISO 14041	Life cycle assessment—inventory analysis	Publish early 1999
ISO 14042	Life cycle assessment—impact assessment	Publish early 1999
ISO 14043	Life cycle assessment—interpretation	Publish early 1999
ISO 14049	Examples for application of 14041	Draft published June 1998
ISO 14050	Environmental management vocabulary	Final standard as of May 1998
ISO 14061	Information to assist forestry organizations	Publish mid 1998
Guide 64	Inclusion of environmental aspects in product standards	Published March 1997

* As of October 1998.
Source: *TC207* web page [5].

As stated previously, ISO 14000 has yet to catch on in the United States. There is a great deal more interest in Europe and Japan than in this country. Some things could change this outlook, however. Many organizations are waiting to hear formal policy from the Environmental Protection Agency (EPA) regarding ISO 14000. It is difficult for EPA to fully endorse ISO 14000 because an organization can be registered to ISO 14000 and demonstrate a commitment to compliance with regulations without being in compliance with all regulations. For this reason, while EPA has been quite involved throughout the process of developing the ISO 14000 standards, it has not formally endorsed the standards or provided overwhelming incentives to implement an EMS. Until EPA does make a formal statement regarding ISO 14000, organizations will have to decide individually whether the other motivations for implementing an EMS are reason enough to continue.

ISO 14001—SPECIFICATION STANDARD

The ISO 14001 specification standard specifies the requirements for an environmental management system and follows the continuous improvement cycle (modified Deming cycle) of Plan-Do-Check-Act (see Fig. 6.9.1). The main topic areas of the standard are

1.0 Scope
2.0 Normative References
3.0 Definitions
4.0 Environmental Management System Requirements
  4.1 General Requirements
  4.2 Environmental Policy
  4.3 Planning
  4.4 Implementation and Operation
  4.5 Checking and Corrective Action
  4.6 Management Review

The following definitions, taken directly from ISO 14001, may help the reader understand these requirements [6]:

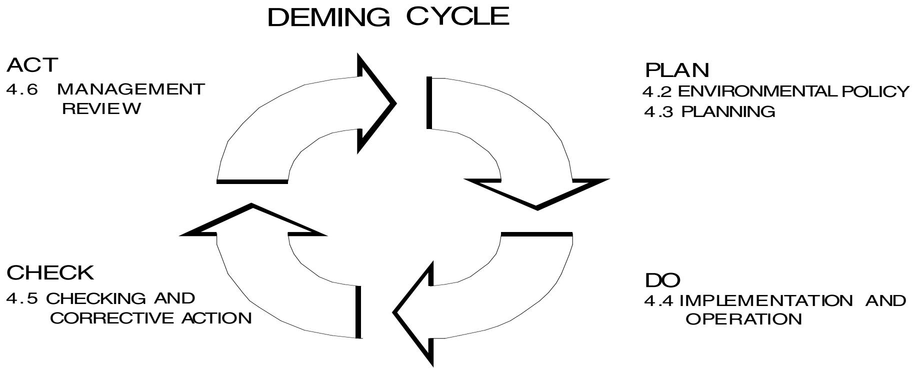

FIGURE 6.9.1 Continuous improvement cycle.

Environment: Surroundings in which an organization operates, including air, water, land, natural resources, flora, fauna, *humans,* and their interrelation.

Continual improvement: Process of enhancing the environmental management system to achieve improvements in overall environmental performance in line with the organization's environmental policy.

Environmental aspect: Element of an organization's activities, products, or services that can interact with the environment.

Environmental impact: Any change to the environment, whether adverse or beneficial, wholly or partially resulting from an organization's activities, products, or services.

Environmental management system (EMS): The part of the overall management system that includes organizational structure, planning activities, responsibilities, practices, procedures, processes, and resources for developing, implementing, achieving, reviewing, and maintaining the environmental policy.

Prevention of pollution: Use of processes, practices, materials, or products that avoid, reduce, or control pollution, which may include recycling, treatment, process changes, control mechanisms, efficient use of resources, and material substitution.

The primary section (section 4.0) that describes the required elements of an environmental management system is titled Environmental Management System Requirements. A discussion of these requirements will follow.

General Requirements (section 4.1). This section briefly states that an organization must establish and maintain an environmental management system meeting the requirements of ISO 14001.

Environmental Policy (section 4.2). The policy and planning sections describe the Plan portion of the continual improvement cycle. An environmental policy statement that is appropriate to the nature, scale, and environmental impacts of an organization's activities, products, or services is required. This policy statement must also include a commitment to continual improvement of the management system, commitment to prevention of pollution, and commitment to comply with all relevant environmental legislation, regulations, and other requirements. The policy statement provides the framework for setting and reviewing environmental objectives and targets and must be documented, communicated to all employees, and made available to the public.

Planning (section 4.3). The planning effort sets the framework for the entire environmental management system. The main requirements are that an organization establish and maintain procedures to consistently evaluate the environmental aspects (elements of its services, products, or activities that can interact with the environment) and ensure that the aspects related to significant environmental impacts are considered in setting its environmental objectives. The following example illustrates the different meanings of aspects, impacts, objectives, and targets.

There are many concerns regarding the operation of a poultry processing plant, but a major concern is water usage. An *aspect* of their manufacturing process is water usage. The *impact,* which may be significant, is that their water usage depletes the overall drinking water resources available to the community. They might set an *objective* to reduce the usage of water in their operation through various changes in working practices and equipment modifications. A *target* of reducing water usage by 20 percent within one year has been established.

How an organization establishes its aspects, impacts, objectives, and targets will play a major role in determining the overall effectiveness of the environmental management system. ISO 14001 allows a great deal of flexibility for an organization to include the following items as aspects of their manufacturing operation:

- Environmental compliance
- Prevention of pollution
- Sustainability
- Resource/energy conservation
- Product interaction with the environment
- Transportation issues
- Occupational safety and health issues

An organization must choose carefully the terminology it uses with respect to prevention of pollution in its policy statement. Pollution prevention is part of the EPA waste reduction hierarchy and includes only source substitution and closed-loop recycling. A firm that sends solvents off-site for recycling, therefore, could have its policy statement challenged if it commits to pollution prevention.

Additionally, an organization is required to establish and maintain a procedure to identify and have access to legal and other requirements that are applicable to its environmental aspects. Objectives and targets must be documented at each relevant function and level within the organization. Special care must be taken to ensure that these objectives and targets are consistent with the environmental policy. The environmental management program must be established to achieve the established objectives and targets. This includes the designation of responsibility for achieving objectives/targets at each relevant function and level of the organization and the means and time frame by which they are to be achieved.

Implementation and Operation (section 4.4). This section describes the requirements for the Do portion of the continual improvement cycle. The elements of this section include

- Responsibility
- Training
- Communication
- Environmental management system documentation
- Document control
- Operational control
- Emergency preparedness and response

This section describes how the framework of the environmental management system should look. Some highlights of this section include the management representative and the management system documentation. An organization wishing to conform with ISO 14001 is required to designate at least one management representative to facilitate implementation and communicate the status of continual improvement efforts to management. The requirements regarding management system documentation basically include a requirement to document the core elements of the management system and to provide guidance to all related documentation such as procedures, work instructions, and records. While there is no strict requirement to have an environmental manual, the documentation requirements must be met. Some third-party auditors may prefer or even require environmental manuals, so an organization is advised to check if it is pursuing registration. Additional requirements include establishing and maintaining procedures for internal communication between various levels and functions of the organization and procedures for receiving, documenting, and responding to relevant communication from external interested parties.

Documents required by ISO 14001 must be controlled to ensure that they can be located, periodically reviewed and revised (as necessary), approved for adequacy by authorized personnel, and available in their current version. Special consideration must also be taken to ensure that obsolete documents are either removed or identified as obsolete if retained for legal purposes.

In addition to document control, the organization has to maintain control over operations and activities that are associated with the identified environmental aspects in line with its policy, objectives, and targets. To achieve this control, the organization must establish and maintain documented procedures to cover situations where their absence could lead to deviations from the environmental policy and objectives/targets, stipulate operating criteria in the procedures, establish and maintain procedures related to environmental aspects, and communicate relevant procedures and requirements to suppliers and contractors.

Finally, an organization must establish and maintain procedures related to preventing and responding to accidents and emergency situations and review and revise these procedures where necessary. The organization must also test these procedures periodically where practicable.

Checking and Corrective Action (section 4.5). This section describes the Check portion of the continual improvement cycle. The main requirement in this section is that an organization perform periodic environmental management system audits to ensure that the system conforms to ISO 14001. The results of these audits must be communicated to management to ensure that any necessary corrective action takes place. Additionally, an organization must establish and maintain a documented procedure for periodically evaluating compliance with relevant environmental legislation and regulations.

Management Review (section 4.6). This section describes the Act portion of the continual improvement cycle. A review of the environmental management system must be conducted periodically by top management to ensure that the system is suitable, adequate, and effective. Again, any necessary changes to the policy, objectives, and other elements of the EMS must be made as a result of this review.

ISO 14000 IMPLEMENTATION—GENERAL ISSUES

As one can well expect, implementing an environmental management system within an organization is hardly something to be taken lightly. As with many of its predecessors such as total quality management (TQM), material requirements planning (MRP), and just-in-time (JIT) manufacturing, implementing an EMS involves a cultural change and therefore requires full commitment at all levels of the organization. Once the decision to implement an environmental management system has been made, some other decisions should be made initially to make the process easier. First, the scope of the environmental management system (EMS) should be determined. Issues such as whether to include occupational health and safety aspects as part of the management system should be considered and addressed at this point. Second, decisions regarding registration should be made. Many organizations are implementing ISO 14000–like systems with no intentions of getting registered initially but with a desire to consider registration at some point in the future. There is nothing wrong with this approach, but if registration is a known goal, it may help with implementation for the organization to be in contact with the chosen registrar and understand its own individual requirements. Finally, if an organization is already registered to one of the ISO 9000 standards, the environmental management system project team can learn and gain a great deal from the quality management system team. Areas such as implementation and checking/corrective action are very similar, regardless of whether environmental or quality is the ultimate result. Many of the companies considered in the case studies section of this chapter made the mistake of reinventing the wheel because their environmental and quality teams did not communicate with each other.

One of the implementation issues mentioned earlier deals with occupational safety and health. While it is perfectly acceptable to include safety and health aspects within the overall

EMS, a safety and health ISO standard is unlikely to emerge any time soon. At least two separate meetings were conducted in 1996, one in Chicago and the other in Geneva, to discuss the need for an international occupational health and safety management system standard. Standards are even available from the British Standards Institute (BSI) and the American Industrial Hygiene Association (AIHA) that provide guidance on implementing such a system. The outcry from the 1996 meetings, however, was a resounding "no" for developing another standard. It is impossible to provide an account of all the responses, but many thought it was too soon after ISO 14000 to consider an occupational health and safety management system standard. Regardless, ISO 14000 leaves wide open the prospect for safety and health aspects to be included in an EMS.

Another compelling implementation issue is compliance versus conformance. Unlike its 9000 cousin, ISO 14000 deals with an area that is highly regulated by governments around the world. ISO 14000 requires an organization to *commit to compliance* with all relevant regulations, legislation, and any other organization's (e.g., Chemical Manufacturers Association [CMA] Responsible Care Program) requirements. An auditor's only responsibility is identifying that commitment, not performing a compliance inspection. Another requirement is that an organization implement a procedure for ensuring current regulatory information. This whole area is subject to a tremendous amount of interpretation on the part of third-party auditors. Commitment to compliance is difficult to demonstrate without at least looking at the details of the compliance management system. It would be easy, however, to get bogged down in the compliance world and forget that the management system is the focus of the audit. As is typical, the answer probably lies somewhere in between. Auditors with detailed compliance backgrounds will have to be careful not to get dragged off course into a compliance audit, and those with little compliance background will have to learn the language of compliance to determine whether a commitment to comply exists.

When considering implementation, an organization also needs to determinate aspects, impacts, objectives, and targets. This activity sets the framework for the environmental management system and will greatly determine whether the system ultimately improves outputs such as environmental performance and compliance or just results in a certificate hanging on the wall stating how wonderful the organization is environmentally. While it is ultimately up to the registration system (registrars and accreditors) to maintain the integrity of ISO 14000, each organization should consider it their responsibility to aggressively establish the agenda for the management system. ISO 14001 does not specifically state the number of aspects required, the nature of determining significance of impacts, the number of objectives required, or the level of improvement for targets that must be achieved. This is a flexible standard meant to adapt to many types of facilities and processes, so the registrars will have to answer questions related to whether an organization is truly trying to improve their environmental impacts or just paying lip service to an emerging hot topic.

ISO 14000 IMPLEMENTATION—SPECIFIC GUIDANCE

The previous section identified some of the general implementation issues that have been, or might be, experienced with respect to implementing an environmental management system such as the one specified in ISO 14001. This section goes into more detail with some of the specific requirements contained in ISO 14001 and provides guidance on implementation. Much of the information in this section is speculative since there have been only a handful of registrations in the United States at the time of this printing.

The starting point for the environmental management system is the policy statement. The first recommendation regarding the policy statement is simple: read the requirements in ISO 14001 and make sure they are followed. The three required commitments—continuous improvement, prevention of pollution, and compliance with relevant regulations and legislation—must be included in the policy statement. Additionally, the policy statement has to be documented, communicated to the employees, and made available to the public. Other implementation guidance regarding the policy statement is not quite as clear. Since the policy statement provides the framework for the management system, all other aspects of the management system lead back to the policy statement. For example, if the policy statement focuses solely on aluminum can recycling, but the aspects, impacts, objectives, and targets focus on wastewater treatment, there is a disconnect in the overall system. Therefore, the policy statement should be an accurate overall reflection of how the organization views its role with respect to the environment and how it can improve on significant impacts. As with any policy statement, it is best to consult the legal community for recommendations. For instance, if the policy statement reads, "We will comply with all federal regulations," and there is even one instance where, even in good faith, the organization missed a minor technicality with a regulation, then the statement is suspect. The use of broader statements with respect to policy is recommended to ensure that the organization can actually achieve what it says it will.

There is virtually an infinite number of methods for determining environmental aspects. Most organizations will start with compliance-related areas to ensure legal responsibilities are addressed. Others will look to preventing pollution through typical means such as source reduction, process improvement, material substitution, or on-site recycling. If these methods are not available, more efficient waste treatment methods or off-site recycling options may need to be considered. Issues associated with products should not be ignored. For example, the product that is produced by an organization may have a greater adverse impact on the environment than the process by which that product is manufactured.

Identification of Aspects

No single method exists for identifying the aspects for an ISO 14001 EMS. Techniques include simple brainstorming and evaluation of regulatory issues. Two possible approaches to aspect identification are the plant mass balance and a sustainability model such as the Natural Step.

Plant Mass Balance. The concept of the plant mass balance is illustrated in Fig. 6.9.2. The mass balance concept is to identify the final destination of raw materials brought into the plant. A production plant converts raw materials into products. Raw materials that are not converted into products leave the plant as air emissions, wastewater, or solid waste. The plant loses revenues since this raw material is not converted into salable product. In addition, the plant may have costs for the treatment and disposal of these wastes.

It is not sufficient to simply know what the raw material is. A plant must know the composition of the raw material. For example, if the raw material is a solvent-based paint, surface preparation, or other substance containing xylene, some of the xylene may be released as an

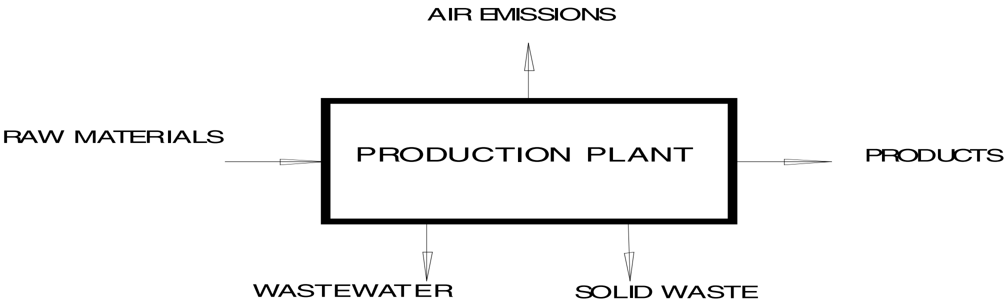

FIGURE 6.9.2 Plant mass balance.

air emission. Xylene is both a volatile organic compound (VOC) and a hazardous air pollutant (HAP). If the raw material is a water-based coating containing latex, some of the latex may be released in wastewater. Latex puts a chemical oxygen demand (COD) pollutant loading in wastewater.

Material safety data sheets (MSDSs) provide some information about raw material composition. The regulations require that these MSDSs identify chemicals that are reportable under the Toxic Release Inventory (TRI) requirements of the Emergency Planning and Community Right-to-Know Act (EPCRA). However, a facility may have to get additional information or conduct testing to get a complete characterization of a raw material.

The mass balance concept requires that a production plant identify where and in what form all constituents of the raw materials that are brought into the plant leave the plant. If a constituent does not leave as product, a determination must be made as to whether the release is a regulatory issue. The materials exiting the plant as wastes then become the environmental aspects of the facility.

A facility should also include data on the energy required for raw material processing. This will provide a complete mass and energy balance of the facility. The cost savings potential of either a mass or a complete mass and energy balance can provide the economic driver for an EMS.

Sustainability. One method for using sustainability to determine environmental aspects as well as significant impacts, objectives, and targets would be to compare production plant operations to a model. One such model is the Natural Step (TNS) developed by Swedish physician Karl-Henrik Robert [7]. TNS is based on four system conditions:

1. Substances from the Earth's crust must not systematically increase in nature.
2. Substances produced by society must not systematically increase in nature.
3. The physical basis for the productivity and diversity of nature must not be systematically destroyed.
4. There must be fair and efficient use of resources with respect to meeting human needs.

A facility using TNS would review all of its operations and evaluate whether each of the four system conditions were met by the operation. If a particular operation did not meet one or more of the system conditions, it would be identified as having a significant impact, and objectives and targets would be established to change the operation so that the system conditions would be met. Once all operations met all system conditions, the EMS would then be modified to ensure that the company continued to meet these conditions, particularly with the introduction of new products and services.

Natural extensions of the environmental aspects/impacts are the objectives and targets. Once the impacts on the environment are determined, the next step is to take action to determine how to decrease adverse impacts or increase beneficial impacts. A good place to start with the objectives and targets is to simply review the regulatory requirements for the facility and ensure that all requirements are met. This is easy to say but not always easy to put into practice. The purpose of an environmental management system is far broader than just compliance, but it is difficult to put any priority on nonregulatory areas when there are holes in the regulatory system. The best approach is to implement a systematic compliance management system within the environmental management system to ensure that all regulatory requirements are met. Components of this compliance management system will most likely include periodic audits, systematic updates of regulatory requirements, incentives and disciplinary action for personnel to meet regulatory requirements, training for personnel on regulatory requirements, and the like. Once the regulatory areas are covered, a facility can go beyond compliance and look for other areas where it can benefit the environment. The ISO 14001 standard requires the organization to identify a procedure to continuously reevaluate aspects/impacts/objectives/targets, so this is not a one-shot deal. Even though a certain aspect is not considered a priority currently, it may become one after the initial round of objectives and targets is met. Finally, philosophical differences may affect how an organization goes about setting objectives and targets. Some individuals would prefer to set targets at levels that couldn't possibly be attained—to have that goal to shoot for in continuous-improvement mode. Others would prefer to set targets at achievable, reasonable levels and set new targets once these have been achieved. Regardless of philosophy, targets should be measurable to monitor progress.

Structure and responsibility is the section in ISO 14001 that describes how the organization plans on achieving the objectives and targets that have been set. This is one area where organizations that have implemented one of the ISO 9000 standards really gain an advantage over those that have not. The main thing that has to be considered is that individuals must make the environmental management system part of the overall culture of the organization, and that is not likely to happen automatically. For this reason, individuals have to be held accountable for following procedures that will eventually lead to meeting the established objectives and targets. A good place to start is to ensure that individual job descriptions contain detailed responsibilities with respect to the environmental management system. Additionally, organizational charts should identify the responsibilities of personnel regarding the EMS. Finally, it should be quite clear who is accountable for what, with respect to the environmental management system; not to overemphasize the negative discipline: positive reenforcement is always recommended. As part of the overall management system documentation, recognition and awards for peak performers in the environmental area can be very effective.

ISO 9000 companies have an established training program developed through needs analysis. Companies that do not have an ISO 9000 system will have to develop such a training program to meet the requirements of ISO 14001. The best guidance for training is to follow the requirements in ISO 14001 and document every step. One of the problems with training is that unless a feedback element is included in the system, it is very difficult to determine whether the training has been effective. Tests and demonstrations of competence should be an integral part of any training program and is essential to ISO 14000 implementation. Specifically, employees must know which significant impacts may be affected by their work activities and what the implications of nonconformance might be. As with other areas of ISO 14001, it is best to establish training procedures and schedules and ensure that they are followed. Documentation is a very important component to ISO 14000 implementation. While the strict requirements for documentation are not as severe as with 9000, if an organization is pursuing registration it must have something to show the auditors to prove it is following a system of environmental management. Procedures, work instructions, and various records will most likely be elements of the documentation system. Document control is also of primary importance. Some elements to include in document control are the issue/revision date, effective date of document, approvals, revision number, document number or name, copy number, and any cross-references to other documents. While ISO 14001 does not specifically require all these elements, the general requirement is that any relevant records can be located, maintained, and kept up to date.

The final requirement related to operating the environmental management system deals with emergency preparedness and response. Requirements here are quite typical—to ensure that the organization has evaluated the various types of emergency situations that could arise, has developed plans to prevent these types of emergencies, and has developed and practices various response actions. One of the most important elements of emergency response is conducting periodic drills to ensure that personnel will be able to respond appropriately should an emergency situation arise. Another commonly overlooked element is conducting a "what-if" analysis to ensure that all potential problems are considered. Examples of things that are frequently considered include power outages and their effects on emergency response equipment, employees or other personnel (for example visitors) with disabilities, and accidents other than fire or chemical release such as tornadoes, workplace violence, and medical emergencies. Management review is the final portion of the continuous improvement loop required by ISO 14001. The most important recommendation here is that upper management truly become involved in the process of evaluating the management system and ensuring correction of any nonconformities or other problems. All too often, management agrees to these programs with little direct involvement in finding solutions to problems. One of the most important jobs of the management representative, although quite difficult, is to ensure that management is involved and providing support every step of the way.

ENVIRONMENTAL MANAGEMENT SYSTEM AUDITS

Several different types of audits are associated with an environmental management system. These audits vary in scope, frequency, personnel involved, time, and other factors. All of these audits involve costs either for the time of company staff or the cost of an external registrar. A brief description of the various types of audits follows.

Internal Audits. Internal audits are a requirement of the ISO 14001 standard. Most registrars require that each function of the company that is associated with the EMS be audited at least once per year. Functions whose activities relate to the significant impacts may be audited on a more frequent basis. In addition, functions where major nonconformities are found during either internal or external audits should be audited more frequently. While the ISO 14001 standard does not require internal auditor independence (required by ISO 9000), it is highly recommended. The audits typically last only a couple of hours, but tracking of the time required of both the auditor and auditee is suggested.

Gap Analysis Audit. A gap analysis audit is the first step in the implementation of an ISO 14001 EMS. Taking about one day, it is usually conducted by auditor(s) external to the company who are familiar with the requirements of the standard. It usually begins with a brief tour of the facility to familiarize the auditors with the operation. The audit is a desk audit, and documentation is usually not reviewed unless it is readily available. The auditors use a checklist that breaks the standard down into specific questions. The audit determines whether the standard requirements exist at the facility and are documented. The audit is often more of a training session since some of the terminology of the standard such as *environmental aspects* may be foreign to the auditee. For example, auditors have found that when they explain what an environmental aspect is, this item often exists at the facility and is documented. However, the facility may refer to the aspect under a different term.

Baseline Audit. The baseline audit is conducted after the facility has developed some of its documentation. Auditors have found that a facility should not complete its documentation since problems identified during this audit could necessitate the rewriting of some of this documentation. The audit typically requires two to four auditors and takes one to two days. The auditors review the documentation that has been generated and interview workers on the floor.

Preassessment Audit. The preassessment audit is a mock registration audit. It should be conducted after the complete EMS is implemented and the documentation is complete. The audit requires two to six auditors and two to three days depending on the size of the facility. The audit includes a review of documentation selected randomly and interviews with floor personnel. Facilities may have these audits conducted by their registrar, an independent organization, or both. Having a "tough" independent auditor is often recommended since this will help the facility for the registration audit. Major and minor nonconformities are documented and included in an audit report to the facility.

Registration Audit. At the registration audit, an accredited auditor determines if a facility will be recommended for registration. Accredited auditors work for registrars who are accredited by the Registrar Accreditation Board (RAB) and the American National Standards Institute (ANSI) in the United States. By mid-1999, there were five accredited ISO 14000 registrars in the United States. A registrar uses an accredited lead auditor and accredited auditors on the team. The number of auditors and the number of audit days typically depend on the number of employees at the company. At the conclusion of the audit, the audit team will either recommend or not recommend a company for registration. Some registrars will recommend a company for registration with a provision that major nonconformities identified during the audit be corrected.

Surveillance Audits. Surveillance audits are typically conducted every six months by a registrar. The number of auditors and audit days depend on the number of employees in the company, but are typically less than for the registration audit. A company should anticipate that any area where either major or minor nonconformities were identified will be carefully audited at this time.

Reregistration Audits. These audits may be required by some registrars. The frequency varies, but five years might be typical. Often the surveillance audit is the only requirement after initial registration.

CASE STUDIES

The case studies present an overview of audits of the ISO 14000 EMS implemented at eight industrial facilities in the southeastern United States. The studies provide an overview of the processes at each facility and indicate the status of any ISO 9000 quality system at the facility. The case studies describe the length of the audit and present the key findings. Finally some indication of the next step for each facility is presented.

Company 1 is a textile manufacturer that produces backing for carpets and other woven material. The company is registered to ISO 9000 and had already generated a significant portion of its documentation. The key findings of the two-day baseline audit were as follows:

- The company had developed an EMS manual.
- The company had generated an extensive list of environmental aspects, but had not prioritized these aspects to determine significant impacts. As a result, the oils used for both machinery and fabric lubrication, the most significant issue at the plant, were not specifically spelled out as the significant impact at the facility.
- Several procedures were written by the management team rather than the floor personnel. As a result, there were differences between the operations on the floor and the documentation.
- Training was the usual method by which plant personnel knew how to perform their jobs. Floor supervisors indicated that records were maintained in the training office, but the training office had no such records. It is generally recommended that task-related training records be maintained by the floor supervisors.

Since the completion of the baseline audit at Company 1, the company has successfully achieved registration under ISO 14001.

Company 2 is a carpet manufacturer that is considering an integrated ISO 9000/14001 system. A one-day gap analysis was conducted at the facility with one 2-auditor team evaluating the quality system and a second 2-auditor team evaluating the environmental management system. The key findings of both one-day gap analysis audits were as follows:

- More documentation appeared to exist for the environmental system than for the quality system. However, the link between the ISO 14001 requirements and the existing environmental documentation appeared to be missing. Although an EMS manual is not required by ISO 14001, it is apparent that such a manual is needed to prove conformance to the standard. It should be noted that the 1987 version of the ISO 9000 standard did not require a quality manual although later revisions did.

- Even though environmental documentation existed, there appeared to be a problem with document control because a system did not exist for either quality or environmental. The implementation of a document control system will be a major issue for the company.

Company 2 is just starting the process of implementing management systems for both ISO 9000 and 14001. The company also has a special interest in sustainability issues as an aspect. This company is just beginning the process and so much work is still needed. Concurrent development of both the ISO 9000 and 14000 is recommended.

Company 3 is a manufacturer of equipment for the aerospace industry that is registered to ISO 9001. A one-day gap analysis was conducted at the facility by a four-auditor team. The team split into two groups to evaluate separate requirements of the ISO 14001 standard with different plant personnel. The key findings of the one-day gap analysis audit were as follows:

- The company had a written environmental policy that appeared to meet all of the requirements of the standard. The policy was posted throughout the plant, and apparently a good part of the EMS was already in place.
- The company had extensive documentation of its environmental procedures and its document control system met the requirements of the standard. In addition, the company had extensive records to prove that these procedures were being implemented. This was probably due to the requirements of the aerospace industry.
- The link between the company documentation and operations and the ISO 14001 standard was not evident. It again appeared that an EMS manual was needed to prove the existence of an EMS to an auditor.
- The method of identification of environmental aspects was somewhat unusual in that these were often dictated by corporate instead of plant management. In addition, corporate management specified objectives and targets. However, the facility has the responsibility to review and modify these aspects to the specific operations and needs of the facility. Since the standard does not dictate the procedure for determining aspects, significant impacts, objectives, and targets, the system appeared to be in conformance with the standard as long as it could be documented.
- The environmental personnel apparently had not yet tapped the resources of the quality operations at the facility. Working with these groups could quickly resolve the deficiencies in the internal auditing and in the corrective and preventive action requirements.

Company 3 plans to move ahead with the continued implementation of an EMS in anticipation of a future directive from corporate for implementation of the ISO 14001 on a corporatewide basis. Since this company had pieces of an EMS already in place, the development of the written environmental management system manual was recommended.

Company 4 is a manufacturer of components used in the electronics industry and is registered to ISO 9002. The key findings of the one-day gap analysis audit were as follows:

- Although the company had the document control system in place, it had not incorporated the ISO 14001 requirements.
- A rough-draft policy statement had been developed but one of the team members was not aware of it. Also, this statement needed quite a bit of work to include all the required elements (commitment to continual improvement, regulatory, compliance, and prevention of pollution).
- The company had not determined its aspects or significant impacts and could therefore not develop objectives and targets. Its operation was fairly clean; however, solid waste reduction appears to be an aspect with a significant impact.

Since this company was just beginning the process, a significant amount of work was still needed. The establishment of a team to initiate the task was suggested.

Company 5 is a service operation in the communications industry, but does operate several facilities. The key findings of the two-day gap analysis audit were as follows:

- The company had three separate divisions for safety, health, and environmental compliance. These divisions audit for regulatory compliance. The primary purpose of the gap analysis was to determine how the three separate groups might function under an ISO 14001 format.
- Communications appeared to be a key issue in the company, and ISO 14001 might help solve this issue.

The resolution of some basic management and communications problems was recommended before proceeding with the development of an EMS.

Company 6 is a manufacturer of refrigeration equipment. The company is registered to ISO 9002. The key findings of the three-day preassessment audit were as follows:

- Although the company was registered to ISO 9002, document control was a major problem with the ISO 14001 system.
- There were several conflicts between the ISO 9002 quality system, an environmental, safety, and health system required by corporate management, and the new ISO 14001 EMS.
- The aspects and impacts of the EMS included many safety and health issues.
- As was found at Company 1, several procedures apparently were written by the management team rather than the floor personnel. As a result, there were differences between the operations on the floor and the documentation.
- Some people seemed to be more interested in the certificate of registration than in the actual operation of the EMS at the facility.
- Some individuals at the company were difficult to work with.

It appeared that the quality and environmental management teams may not be communicating. It was suggested that these two teams be merged to complete the EMS.

Company 7 is a military base that is responsible for the major repair and overhaul of several models of aircraft. As a result, it has manufacturing operations that have a number of significant environmental impacts. In addition, a reserve flying wing is a tenant organization at the base. The gap analysis included the environmental management directorate, two of the manufacturing operations, and the tenant organization. The key findings of the three-day gap analysis audit were as follows:

- It was not clear that either the management representative or the EMS coordinators within each organization have sufficient authority for the implementation of the system. It appeared that several management representatives (as allowed by the standard) might be necessary.
- The military base views registration to ISO 14001 as a mark of excellence that sets it apart from other bases. This could become important when it competes against other bases for the maintenance and overhaul of other aircraft systems in the future.
- Many procedures mandated by the Department of Defense were already in place. The need for an EMS manual to link these existing procedures was again evident.
- The major system maintenance and overhaul organizations operated somewhat independently. Establishing a seamless EMS could be difficult. The use of multiple management representatives with a lead management representative could solve this problem.
- The very independent tenant organization could be difficult to incorporate into the EMS.

INTERNATIONAL ENVIRONMENTAL STANDARDS BASED ON ISO 14000

The base planned to first have the environmental directorate registered, and then pull the entire base into a registration. The base is just beginning to implement the system. Since this operation was a military base, some direction from higher headquarters was needed before proceeding with the EMS.

Company 8 is a manufacturer of aggregates for the construction industry. The company has numerous facilities and eventually plans to have all of these facilities become registered to the standard. The key findings of the one-day gap analysis audit were as follows:

- The company had an extensive environmental compliance system already in place that included a number of internal audits and other activities required by the ISO 14001 standard.
- An EMS manual appeared to be needed to establish the link between the existing system and the standard requirements.
- The company viewed registration to the standard as providing a competitive edge and a seal of excellence. In addition, the ownership of the company is European, so ISO registration was considered valuable by corporate management.

The company is now in the process of implementing an EMS that conforms to the requirements of the ISO 14001 standard. Additional training and the development of a manual was the next activity for this company.

HOW TO PROCEED

There is no single plan for a facility to have its EMS registered to ISO 14001. Likewise, there is no set time required, although one to two years is generally considered to be typical. The following is a suggested sequence for this process:

1. Have one or more plant managers attend an Executive Introduction course. These are typically one-day courses at minimal or no cost that provide an overview of the EMS standard.
2. Have an external party with experience in ISO 14001 conduct a gap analysis audit. This requires one day and can sometimes be conducted at no cost.
3. Make the decision to implement an EMS and appoint the management representative(s). While an organization should make the final decision to become registered, this decision can be put on hold at this time.
4. Conduct an ISO 14001 In-depth Training Course at the facility. This one-day course should be attended by all facility management and supervisory personnel who will be involved in the EMS. The course is tailored to look at the actual policy, procedures, and operations at the facility. There are costs involved for this training.
5. Have one or more plant personnel attend an ISO 14001 System Documentation Course. The management representative(s) must attend this course. These courses are typically two days in length and cost about $700 per attendee.
6. Have one or more plant personnel attend an ISO 14001 Internal Auditing Course. The management representative(s) must attend this course. These courses are typically two days in length and cost about $700 per attendee.

   Note: The System Documentation Course should be conducted before the Internal Auditing Course since one of the items audited is documentation. These courses can be combined and conducted in-plant for more attendees and reduced costs.
7. Have the management representative(s) attend an ISO 14001 Lead Auditor Course. These courses are typically five days in length. Attendance at an accredited course is not

mandatory but is recommended, particularly if the attendee plans to seek future accreditation as a lead auditor.

8. Begin the implementation of the EMS.

9. Conduct a baseline audit. This should be conducted after some of the EMS documentation has been started but before the documentation is completed in case revisions must be made.

10. Make the final decision to become registered (if this has not already been made) and select a registrar. Be sure and get package bids from registrars that include cost of registration and surveillance audits and travel.

11. Complete the EMS.

12. Conduct the preassessment audit. It may be desirable to conduct two of these audits, one by an outside independent agency and one by the registrar.

13. Conduct the registration audit.

14. Assuming the facility was recommended for registration, immediately begin correction of any major or minor nonconformities identified during the registration audit.

15. Conduct the surveillance audit.

16. Conduct reregistration audits (if required).

SUMMARY

More often than not, industrial engineers find themselves knee-deep in projects as broad as the implementation of an ISO management system. If an organization decides to investigate ISO 14000 as a way of conducting environmental affairs, industrial engineers very likely will be involved in every aspect of that investigation and the ensuing decision. Once implementation of an environmental management system is undertaken, again the industrial engineers are there to help in the process of changing culture. It remains to be seen whether ISO 14000 will become as popular as, or even more popular than, ISO 9000. ISO 14000 is a popular topic at environmental and other international conferences and is gaining much interest. What has not happened yet, at least in the United States, is the wide-scale transfer of this interest into action. The possibility certainly exists for ISO 14000 to become a requirement to do business, making it part of many people's lives. This alone is reason enough to learn more about this standard and decide whether it is worth implementing. There are certainly costs associated with implementation, but a well-implemented and effective system may be able to outweigh these costs. The ultimate hope is that a worldwide network of organizations implementing ISO 14000 will help make a difference globally in attaining true environmental sustainability.

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BIOGRAPHIES

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CHAPTER 6.10

OCCUPATIONAL SAFETY MANAGEMENT AND ENGINEERING

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This chapter deals with safety management and safety engineering fundamentals most relevant to the practicing industrial engineering professional. Safety management issues include a discussion of the importance of safety, occupational safety standards and workers' compensation, the Occupational Safety and Health Administration (OSHA) Act, accident statistics and recordkeeping, accident causation models, and accident investigation methods. Safety engineering issues include the fundamentals of construction safety, electrical safety, fires and explosions, hand and power tools, hazardous materials, material handling and storage, personal protective equipment, radiation, robot safety, and systems safety analysis techniques (including PHA, JSA, FMEA, and fault tree analysis). Reference sources for more detailed information on many of these topics are also included.

INTRODUCTION

During the last half of the nineteenth century, the Industrial Revolution changed production methods in the United States, from craft shops to mechanized factories. This greatly expanded the quantity and variety of products available to the average American. While these changes expanded the magnitude and types of hazards present in the industrial workplace, they also resulted in an increased awareness of the need for industrial safety programs.

The National Safety Council [1] estimates that the unintentional, work-related death rate has decreased from approximately 37 per 100,000 people in the U.S. population in 1933 to just over 4 per 100,000 in 1995. Some of this decrease must be attributed to the recognition of the importance of industrial safety and the implementation or enhancement of industrial safety programs. While this improvement is dramatic, one must also be concerned when reviewing the absolute human and financial cost of work-related injuries, illnesses, and deaths in 1995. The National Safety Council [1] notes the following statistics for 1995:

1. 5,300 workers were killed on the job.
2. 3.6 million disabling injuries resulted from workplace accidents.

3. Deaths and injuries in the workplace cost an estimated $119.4 billion.
4. Each death cost approximately $790,000 and each disabling injury $28,000. Each worker must produce goods or services in the amount of $960 just to offset these accident costs.
5. 75 million days of work were lost due to occupational injuries.

It is important for engineers to realize that the incorporation of safety during all phases and into all levels of an operation (design, implementation, worker training, management, and the like) is cost-effective. Safety is important not only because it is good for the worker or good public relations, but because it pays off in the long run. Accident costs go beyond the accident itself and include medical expenses, workers' compensation, machine downtime, lost production, administration costs related to accident investigation, loss of product, and decreased employee morale, to name a few.

In summary, while progress has been made in reducing the human and dollar cost of occupational accidents, continued emphasis is necessary to protect the life and health of workers while accomplishing the organization's total performance objectives.

Definitions

Accident. An accident is an unexpected event that interrupts the work process and carries the potential for injury or damage. Accidents may or may not result in fatality, injury, or property damage, but they have the potential to do so [2]. An accident may be attributed to a human factor, a situational factor (operations, tools, equipment and/or materials), or an environmental factor.

The following definitions, adapted from Hammer [3], illustrate additional safety-related concepts:

Hazard. A hazard is a condition that has the potential to cause injury, damage to equipment or facilities, loss of material or property, or a decrease in the capability to perform a prescribed function.

Danger. The danger inherent in a situation is dependent on the relative exposure to a hazard. For example a high-voltage transformer is a significant hazard, but may present little danger if locked in an underground vault.

Damage. Damage is the severity of injury or magnitude of loss that results from an uncontrolled hazard. A worker on an unguarded beam 3 meters (10 feet) above the ground is exposed to a similar hazard (potential for fall injury) and is in the same danger (exposure to fall) as a worker on an unguarded beam 30 meters (100 feet) above the ground. The possibility of damage, however, is much greater in the latter case.

Risk. Risk is a function of the probability of loss (danger) and the magnitude of potential loss (damage):

$$\text{Risk} = \text{probability of loss} \times \text{magnitude of potential loss}$$

Safety. Safety is the absence of hazards or minimization of exposure to hazards. Firenze [4] also notes that safety is the control of hazards to an acceptable level.

OCCUPATIONAL SAFETY STANDARDS

History of Safety Standards

In about 1750 B.C., Hammurabi's code presented probably the first written safety guidelines (including a penalty clause): "If a builder constructs a house for a man and does not make it firm and the house collapses and causes the death of its owner, the builder shall be put to death" [3].

The first national safety standards were attempts to deal with boiler explosions. In 1915, specifications established by the American Society of Mechanical Engineers (ASME) were adopted nationwide as a voluntary code for the development and maintenance of boilers.

In 1912, the first general industry safety conference was held in Milwaukee. The following year the National Council for Industrial Safety was organized in New York. Shortly thereafter, the organization was enlarged to include other types of safety, and the name was changed to the National Safety Council. The American National Standards Institute (ANSI) evolved from the National Safety Council. The function of ANSI is to determine when a national consensus relative to voluntary standards has been reached rather than to generate these standards. Consensus is reached by coordinating the development of standards by the national groups and organizations concerned. These consensus standards have often been adopted by state and federal agencies as the basis for government regulations.

Workers' Compensation

In 1911, Wisconsin and New Jersey passed the first workers' compensation laws in the United States. By 1915, 30 states had passed some type of workers' compensation legislation. Initially, workers' compensation laws were declared invalid, a violation of the Fourteenth Amendment. Requiring an employer to pay damages without regard to fault was considered taking property "without due process of law." In 1917, the U.S. Supreme Court, ruling in *White v. New York Central Railroad,* declared that such taking of property, because of the extreme degree of public interest involved, was within the state's police powers. This decision resulted in the remaining states quickly passing their own workers' compensation laws. At present, there are workers' compensation laws in all 50 states, three within the U.S. federal government, and four more for the District of Columbia, Guam, Puerto Rico, and the Virgin Islands.

Government Involvement/OSHA

During the first half of the twentieth century, the federal government's involvement in safety legislation was largely limited to setting safety and health standards for its contractors. The Walsh-Healy Public Contract Act of 1936 provided that contracts in excess of $10,000 entered into by an agency of the United States prohibit the use of materials "manufactured in working conditions which are unsanitary or dangerous to the health and safety of the employees."

Federal legislation during the 1960s was aimed primarily at specific industries. The Construction Safety Act of 1969 required that all federal or federally financed or assisted projects in excess of $2,000 comply with established safety and health standards enforced by the U.S. secretary of labor. The Federal Metal and Nonmetallic Mine Safety Act of 1966 and the Federal Coal Mine Health and Safety Act of 1969 also directed attention to occupational safety and health. The Federal Mine Safety and Health Act, promulgated in 1977, established a single mine safety and health law for all mining operations enforced by the Mine Safety and Health Administration (MSHA) within the Department of Labor.

Occupational Safety and Health Act. On October 29, 1970, Richard Nixon signed Public Law 91-596. This law, the Williams-Steiger Occupational Safety and Health Act of 1970 [5], became effective on April 28, 1971. Its stated purpose is as follows:

> To assure safe and healthful working conditions for working men and women; by authorizing enforcement of the standards developed under the Act; by assisting and encouraging the States in their efforts to assure safe and healthful working conditions; by providing for research, information, education, and training in the field of occupational safety and health; and for other purposes.

The Occupational Safety and Health Administration (OSHA) was established to enforce the OSHAct. OSHA is located within the Department of Labor. Under the provisions of the OSHAct, the National Institute for Occupational Safety and Health (NIOSH) was established within the Department of Health, Education, and Welfare (currently the Department of Health and Human Services). While OSHA is primarily an enforcement agency, the primary functions of NIOSH are to perform safety and health research, develop and establish recommended standards, and facilitate the education of personnel qualified to implement the provisions of the OSHAct.

The regulations relating to the OSHAct are included in Parts 1900–1999 of Title 29 of the Code of Federal Regulations (CFR), and the operation of the Occupational Safety and Health Review Commission (OSHRC) are included in Parts 2200–2499. Major examples of specific exclusions of the OSHAct are state and local government employees, self-employed persons, farms at which only immediate family members are employed, and workplaces already protected by other federal agencies under other federal statutes (operators and miners covered by the Federal Mine Safety Act of 1977, for example). Employers with 10 or fewer full- or part-time employees and certain low-hazard businesses are excluded from the injury and illness recordkeeping requirements of the OSHAct. However, even businesses normally exempt may be required to maintain these records in some circumstances [6].

OSHA Standards. There are three separate sets of standards: General Industry (29 CFR 1910), Construction (29 CFR 1926), and Maritime Employment (29 CFR 1915–1919). Summaries of major portions of the OSHA standards have been prepared by OSHA and are available in digest form. OSHA publication 2201 is a summary of the OSHA General Industry standards [7] and OSHA publication 2202 is a summary of the OSHA Construction standards [8].

Application of the General Duty Clause. In order to consider hazards not specifically included in OSHA standards, OSHA has turned to the provisions of Section 5(a) of the OSHAct, or the General Duty Clause, which states the following:

> Each employer—
> (1) shall furnish to each of his employees employment and a place of employment which are free from recognized hazards that are causing or are likely to cause death or serious physical harm to his employees;
> (2) shall comply with occupational safety and health standards promulgated under this Act.

Traditionally, OSHA measured its performance according to the number of citations issued, not according to the level of safety in the workplace. Also, there was little difference in the treatment of conscientious employers and those who needlessly put their workers at risk [9]. Recently, OSHA has implemented new initiatives for achieving its mission "to assure so far as possible every working man and woman in the nation safe and healthful working conditions" [9]. These initiatives include the following:

1. A fundamental paradigm shift from enforcement to partnership
2. Increasing interaction with business and labor in the regulation promulgation process
3. Focusing on results rather than on red tape

OSHA has had some success with these new initiatives, as evidenced by the Maine Top 200 Program, which emphasizes the shift from enforcement to partnership. First, OSHA selected the 200 companies in Maine registering the highest workers' compensation claims. These firms accounted for only about 1 percent of the state's employers, but accounted for 45 percent of the workplace injuries, illnesses, and fatalities [9]. Each company was given the choice between partnership and the traditional enforcement scheme. Nearly all of the companies chose partnership, which included comprehensive self-audits with quarterly reports to OSHA. Failure to comply with auditing obligations resulted in comprehensive workplace inspection. In the eight years prior to implementing this program, OSHA identified about 37,000 hazards at 1316 work sites. In the past three years, employers participating in the Maine program have identified over 180,000 workplace hazards and corrected 128,000 of them [6,9]. OSHA expects to implement similar programs in other states.

In summary, four governmental units have the primary responsibility to carry out the act:

1. *The Occupational Safety and Health Administration* (*OSHA*) is concerned with national, regional, and administrative programs for developing, and ensuring compliance with safety and health standards. It also trains OSHA personnel. U.S. Department of Labor, Department of Labor Building, 200 Constitution Avenue NW, Washington, DC 20210; (202) 219-8148, http://www.osha.gov.
2. *The Occupational Safety and Health Review Commission* (*OSHRC*) reviews citations and proposed penalties in enforcement actions contested by employers or employees. 1120 20th Street NW, 9th floor, Washington, DC 20036; (202) 606-5100.
3. *The National Institute for Occupational Safety and Health* (*NIOSH*) is a research, training, and education agency. U.S. Department of Health and Human Services, 4676 Columbia Parkway, Cincinnati, OH, 45226-1998; (800) 356-4674, http://www.cdc.gov/niosh.
4. *The Bureau of Labor Statistics* (*BLS*) conducts statistical surveys and establishes methods for acquiring injury and illness data. Division of Information Services, 2 Massachusetts Avenue NE, Room 2860, Washington, DC 20212; (202) 606-5886, http://www.bls.gov.

SAFETY MANAGEMENT

Accident Statistics/Recordkeeping

Accident statistics and recordkeeping are useful to evaluate the safety level of a facility or industry, to determine where to allocate safety resources, and to determine the effectiveness of control methodologies.

Accident Statistics. Traditional accident statistics involve the calculation of frequency and severity rates. *Accident frequency* is the number of incidents that occur for a specific number of hours worked. The American National Standards Institute has traditionally used a base of 1 million person-hours worked. OSHA has established 100 person-years (approximately 200,000 person-hours) as the base for accident statistics [10]. (An OSHA-recordable incident is an illness or an injury that involves lost time, restricted work, or medical care other than minor first aid.) For example, if there were three recordable accidents in a year during which 400,000 hours were worked, the OSHA accident frequency rate would be as follows:

$$\frac{\text{Number of accidents} \times 200{,}000}{\text{Hours of employee exposure}} \quad \text{or} \quad \frac{3 \times 200{,}000}{400{,}000} = 1.5 \text{ accidents per 200,000 hours worked}$$

The same procedure may be used to determine the number of a particular type of accident. For example, in the preceding example, if two of the three accidents resulted in lost workdays, the lost workday injury (or LWDI) rate would be as follows:

$$\frac{2 \times 200{,}000}{400{,}000} = 1 \text{ LWDI per 200,000 hours worked}$$

It is also possible to determine an injury *severity* rate. This can be done by using a measure that involves days lost from the job or days of restricted work activity. If, in the preceding example, the two lost workday accidents resulted in a total of 20 days away from work or on restricted work activity, one measure of severity would be as follows:

$$\frac{20 \times 200{,}000}{400{,}000} = 10 \text{ lost (or restricted) workdays per 200,000 hours worked}$$

ANSI calculations of severity rates assign a fixed number of days to fatalities or permanent partial disabilities.

Recordkeeping. While recordkeeping mechanisms may be established for any number of reasons, the recordkeeping requirements of the OSHAct establish the minimum requirements for most employers. *All* employers subject to the OSHA Act must keep injury and illness records, except the following:

1. Employers with a total of 10 or fewer full-time or part-time employees during the previous calendar year at all the employer's work sites
2. Employers who conduct primary business in one of the Standard Industrial Classifications (SIC codes) specifically exempted by OSHA

Specific state or local requirements may require even these federally exempted employers to maintain similar safety records. OSHA Form No. 200 is the basic log and summary of occupational injuries and illnesses. This form includes information relating to the employer, employee name and work location, type of injury or illness, and the extent and outcome of the injury or illness. Essentially all work-related injuries and illnesses are required to be recorded on the OSHA No. 200, except those requiring only minor first aid (e.g., minor scratches, cuts, burns, and splinters). Work-related injuries and illnesses that require any days of restricted work activity must be noted. Supplemental data relating to the injury or illness must be recorded on OSHA Form No. 101. There are several publications that provide detailed information about recordkeeping requirements, including retention, posting, and so on [11]. OSHA has proposed a new, simplified recordkeeping system for occupational injuries and illnesses. The new system aims to simplify the forms and the classification of injuries and illnesses and is intended to be used as a safety performance tracking tool [12]. In addition to occupational injury and illness recordkeeping, OSHA standards may require that employers maintain records for several of its specific programs, including Lockout/Tagout, Hazard Communication, Confined Space Entry, Bloodborne Pathogens, Hoist Inspection, and so on. Recordkeeping requirements include training logs, certification documents, entry permits, and the like.

Accident Causation Models

Prior to the development of formalized approaches to accident control, accidents were viewed as chance occurrences or acts of God. A variation on this theme is that accidents are inherent consequences of production. These attitudes or approaches yield no information about causation, and they limit solutions to those that mitigate the adverse consequences of the event. Perhaps the greatest handicap to the evolution of a systematic approach to safety is the willingness of people, even those with analytical training, to accept accidents as acts of God and to believe that ". . . the causal sequences involved were those of chance or luck that were incapable of any form of examination beyond mere tabulation" [13].

Accident Proneness. During the 1920–1940 era, the theory of *accident proneness* became popular. It was based on studies indicating that certain individuals had a disproportionate number of accidents. Accident proneness assumes a relatively permanent, personal idiosyncrasy that predisposes the individual to have accidents. The assumed permanence of the idiosyncrasy is an important issue. The tendency to have an accident is actually a function of situational and personal factors that include, but are not limited to, age, health, vision, fatigue, stress, and mental state. The proneness to have an accident is really a function of many situational factors that increase the possibility of an accident during a particular period of time.

Studies purporting to identify accident-prone individuals have often employed incorrect statistical techniques that fail to compare distributions of accidents that happen to "accident-prone" people with distributions of accidents that would occur entirely by chance.

Heinrich's Domino Theory. In 1931, Heinrich [14], after reviewing a large number of insurance claims, noted the following:

1. Industrial injuries result only from accidents.
2. Accidents are caused directly only by the unsafe acts of persons or exposure to unsafe mechanical conditions.
3. Unsafe actions and conditions are caused only by the acts of persons.
4. Faults of persons are created by environment or acquired through heredity.

According to Heinrich, five factors in the chronological accident sequence occur in a fixed, logical order: (1) social environment and ancestry, (2) fault of person, (3) unsafe act, mechanical or physical hazard, (4) accident, and (5) injury. Just as the fall of the first domino in a row causes the fall of the entire row, an injury is caused by the action of the preceding factors. The injury is inevitable unless the series is interrupted by the removal of a factor. If, for example, the unsafe act or mechanical hazard is removed, the accident and the injury will not occur. Heinrich's focus on unsafe acts and conditions affected the direction of industrial safety. Through the exploration of unsafe acts, safety professionals delved into psychology, medicine, biology, sociology, and communication skills. Through the exploration of unsafe conditions, safety professionals performed research in the areas of engineering, physics, and chemistry.

Critics have faulted Heinrich's lack of recognition of multiple causation. For example, a worker's fall from a defective ladder may be attributed to an unsafe act (climbing a defective ladder) or an unsafe condition (defective ladder). These causes may result in disciplinary action against the worker for the unsafe act or in getting rid of the unsafe ladder. Further investigation, however, might result in multiple solutions: an improved inspection procedure, improved training, better assignment of responsibilities, or prejob planning by supervisors. These root causes often relate to the management system and affect not only the accident under investigation, but other operational problems that might cause accidents in the future.

It is important to determine, not only the existence of an unsafe act or condition and how it can be corrected, but why it was permitted and whether supervision and management personnel have the knowledge and resources to prevent it.

Systems Engineering Approach. *System safety* has been defined as "the total set of men, equipment, and procedures specifically designed to be imposed on an industrial system for the purpose of increasing safety" [15]. These techniques can be applied to three areas:

1. The design of the end product for safety
2. The design of the manufacturing process for safety
3. The design of the safety system (i.e., the overall perspective, emphasizing the entire management system)

Where traditional industrial safety focuses on the operational phase, the systems approach also includes the conceptual, design, and disposal phases. This approach is based on the assumption that the system consists of an interacting set of discrete elements (human, mechanical, situational, environmental) and that controls can be developed so that the system can perform its function safely. Specific systems-safety analysis techniques will be discussed later in this chapter.

Accident Investigation

Accident investigation involves the investigation of every factor relating to an accident in order to determine the events leading up to and the cause(s) of the accident. There are two primary goals of accident investigation: (1) to determine the cause(s) of the accident and (2) to prevent the accident (or similar accidents) from happening again. The investigator should have a basic familiarity with the equipment or processes and the working conditions and should get to the scene promptly to gather facts and reduce the likelihood of additional accidents/injuries from the same conditions. Data gathering can be accomplished with photography, interviews, accident reconstruction, sketches, and so forth. It must be recognized that accidents often have multiple causes and may be a combination of personal, environmental, procedural, physical, and other factors. It is important to determine if a violation of a safety standard or policy was a factor so that training or enforcement procedures can be modified or appropriate guidelines developed.

A list of the basic equipment required for accident investigations, based on that recommended for OSHA compliance officers, includes personal protective equipment (PPE) necessary to enter the workplace and accident scene (safety glasses, respirators, safety shoes, hearing protection, etc.); photographic and/or sketching equipment, sample-collection media (containers, bags, industrial hygiene sampling gear, etc.); measuring and data-collection devices (stopwatch, tape measure, compass, tape recorder, etc.); and any necessary logs, forms, or checklists used by the company to ensure a thorough investigation.

It is important to investigate accidents as quickly as possible, while both memories and potential evidence are still fresh. Accident scenes should be controlled, first by eliminating the hazards that led or contributed to the accident as well as those that may have resulted from it. After the danger has been controlled, the scene should be left as undisturbed as possible to facilitate investigation of the conditions that resulted in the accident. The pressures to clean up and resume production make photography a useful tool for accident investigation.

Every accident should be investigated to determine the causal factors that may have contributed to it. Accidents can result in injuries, illness, death, facility and equipment damage, interruption of facility operations, or any combination of these. The investigation of minor or near-miss accidents can often provide as many constructive conclusions as the investigation of more serious accidents. Forms can facilitate the collection of accident investigation information and may vary based on the company's needs, but in general forms should include the following information:

1. All available information about the injured person (name, employee identification number, nature of injuries, etc.)
2. A narrative description of the accident, including what the injured person was doing at the time of the accident and, if different, what the person was supposed to be doing
3. The techniques used by the employee to perform the operation and, if different, the standard operating procedures (SOPs)
4. The training the employee had received
5. A description of tools, equipment, and personal protective equipment used and an examination or inspection of these
6. The physical conditions and work environment existing at the time and place of the accident
7. The past accident record of the employee and work area
8. Corrective actions outlined to prevent reoccurrence

Training

Personnel injured at work often lack the information, knowledge, and skills required to protect themselves. OSHA [16] notes that various surveys by the Bureau of Labor Statistics have found the following

1. Of 724 workers injured while working with scaffolds, 27 percent indicated that they had received no information on the use of the scaffold they were using.
2. Of 868 workers suffering head injuries, 71 percent said that they had received no training regarding the use of hard hats.
3. Of 554 workers hurt while maintaining equipment, 61 percent indicated that they had received no training on lockout procedures.

OSHA urges employers to make safety training an essential part of new employee orientation and plant routine. OSHA standards require specific training in many types of hazardous work. An effective, comprehensive training program will result in increased efficiency, reduced absenteeism, and decreased workers' compensation costs.

Safety training material is available from a wide variety of commercial sources. The following information on safety and health training is available from government sources:

1. A catalog, *OSHA Publications and Audiovisual Materials,* is available from the OSHA Publications Office, U.S. Department of Labor, 200 Constitution Avenue NW, Room N3101, Washington, DC 20210; (202) 523-9655, http://www.osha.gov/oshpubs.
2. A six-part self-study program, *Principles and Practices of Occupational Safety and Health,* for first-line supervisors, is available from the Government Printing Office, Superintendent of Documents, P.O. Box 371954, Pittsburgh, PA 15250-7954; (202) 512-1800, http://www.access.gpo.gov/su_docs.
3. A book, *A Resource Guide to Worker Education Materials in Occupational Safety and Health,* lists training materials and publications on safety and health available from some public and private organizations. It may be purchased from the Government Printing Office, Superintendent of Documents, P.O. Box 371954, Pittsburgh, PA 15250-7954; (202) 512-1800, http://www.access.gpo.gov/su_docs.
4. The OSHA Training Institute provides training for industrial personnel in the areas of general industry and construction safety. Tuition is modest, but participants must register in advance. Space may be limited, as there is high demand for some classes. Information is available from The OSHA Training Institute, 1555 Times Drive, Des Plaines, IL 60018-1548; (847) 297-4913, http://www.osha-slc.gov/Training.

Cooperation Between Management and Workers. To be effective, safety programs must involve both management and workers. A quote from the OSHA *Safety and Health Guide for the Meatpacking Industry* [17] illustrates this point:

> An employer's commitment to a safe and healthful environment is essential in the reduction of workplace injury and illness. This commitment can be demonstrated through personal concern for employee safety and health, by the priority placed on safety and health issues, and by setting good examples for workplace safety and health. Employers should also take any necessary corrective action after an inspection or accident. They should assure that appropriate channels of communication exist between workers and supervisors to allow information and feedback on safety and health concerns and performance. In addition, regular self-inspections of the workplace will further help prevent hazards by assuring that established safe work practices are being followed and that unsafe conditions or procedures are identified and corrected properly. These inspections are in addition to the everyday safety and health checks that are the routine duties of supervisors. Since workers are also accountable for their safety and health, it is extremely important that they too have a strong

commitment to workplace safety and health. Workers should immediately inform their supervisor or their employer of any hazards that exist in the workplace and of the conditions, equipment and procedures that would be potentially hazardous. Workers should also understand what the safety and health program is all about, why it is important to them, and how it affects their work.

SAFETY ENGINEERING

Safety engineering may be thought of as the application of engineering and management principles to systems consisting of workers, equipment, materials, and processes within a defined environment, with the goal of reducing the probability and severity (risk) of injuries and property damage. The basic principles relating to safety engineering are presented here.

The Safety Professional

Whether the safety professional is called a safety engineer, safety director, loss control manager, or by some other title, he or she normally functions as a specialist at the management level. The safety program should, but rarely does, enjoy the same position or status as other established activities of the organization, such as sales, production, engineering, or research.

The safety program involves occupational health, product safety, machine design, plant layout, security, and fire prevention. The position of safety professional combines engineering, management, preventive medicine, industrial hygiene, and organizational psychology. It also requires a knowledge of systems safety and ergonomics. The safety professional must have a thorough knowledge of the organization's equipment, facilities, and process and must be able to communicate effectively and work with all types of people.

The emphasis in this area is reflected in the growing membership of the American Society of Safety Engineers (ASSE). This organization has nearly 33,000 members, including over 3,000 *new* members added during the 1996–1997 year [18]. In 1968, the ASSE was instrumental in forming the Board of Certified Safety Professionals (BCSP). The purpose of the BCSP is to certify qualified safety professionals who meet strict educational and experience requirements and who pass a series of rigorous examinations.

Construction Safety

Workers in the construction industry must be protected from many normal industrial safety hazards and additional hazards more common to construction sites, such as open excavations, falling from elevations, falling objects, temporary wiring, excessive dust and noise, and heavy construction machinery. OSHA standards relating to construction are contained in the Code of Federal Regulations (29 CFR 1926). OSHA publication 2202 is a summary of the OSHA Construction standards [8].

Construction safety programs may be thought of as providing for worker safety during the processes of transportation, excavation, fabrication, erection, and demolition.

Transportation. Care must be taken to prevent trucks and other transportation from colliding with or contacting power lines, other vehicles, or other facilities. Traffic patterns in a construction site are often unclear and may vary from day to day. Efforts should be made to establish clear traffic flow patterns and communicate this to all affected personnel. Vehicles with obstructed views to the rear must be equipped with a reverse signal alarm audible above the surrounding noise level, or an observer (spotter) must signal when it is safe to back up [19]. Transporting and handling materials on a construction site is often more dangerous than in a manufacturing environment because there is less control of the workplace (e.g., uneven terrain, weather, multiple contractors, lifting equipment that must be transported and assembled, and deliveries by outside parties).

Excavation. This material is adapted from OSHA publication 2226, *Excavating and Trenching Operations* [20]. For further information, the reader is referred to this document and Code of Federal Regulations, 29 CFR 1926, Subpart P: Excavations.

Excavations and trenching cave-ins are estimated to cause approximately 100 fatalities each year in the United States, and for each fatality there are estimated to be 50 serious injuries. The costs and safeguards for excavation projects are dependent on the traffic, proximity of structures, type of soil, surface and groundwater, water table, underground utilities, and weather.

OSHA requires that all trenches over 5 feet (1.5 meters) deep, except those in solid rock, be sloped, shored, sheeted, braced, or otherwise supported. Trenches less than 5 feet (1.5 meters) deep must be protected if hazardous ground movement is expected. Factors to be taken into account when determining the design of a support system are soil structure, depth of cut, water content of soil, weather and climate, superimposed loads, vibrations, and other operations in the vicinity. The approximate angle of repose for sloping on the sides of excavations ranges from vertical (90° from horizontal) for solid rock, shale, or cemented sand and gravel to a 1.5:1 slope (34° from vertical) for well-rounded loose sand [21].

Fabrication. Fabrication processes at construction sites generally involve the same basic operations as in general industry, but, as discussed earlier, the more variable environment of construction sites can complicate matters. Electrical hazards, explosions, fires, hand, and power tools, and other specific hazards are discussed later in this chapter.

Erection. This material is adapted from OSHA publication 2202, *Construction Industry, Safety and Health Digest* [8]. For further information, the reader is referred to this document and Code of Federal Regulations, 29 CFR 1926, Subparts E, L, M, and R.

The following items, often important issues during the erection of structures at construction sites, are briefly discussed: scaffolds, guardrails and toeboards, ladders, safety nets, and steel erection.

Scaffolds must be able to accept at least four times the maximum intended load and must be erected on a sound footing that is able to accept the maximum intended load without settling [22].

Employees working on scaffolds or platforms must be protected by the use of personal fall-arrest systems or guardrail systems. In addition to hard hats, toeboards provide protection from falling objects. Toeboards must be of substantial construction with openings not to exceed 1 inch (2.5 cm) [22].

Ladders must have uniformly spaced rungs with slip-resistant steps. Ladders should extend at least 36 inches (91.4 cm) above the landing. Portable metal ladders must not be used for electrical work [23].

Safety nets must be provided when workplaces are higher than 25 feet (7.6 meters) above the floor if the use of scaffolds, temporary floors, or other safer procedure is not practical [24].

During steel erection, a temporary floor must be maintained within two stories or 30 feet (9.1 meters), whichever is less, directly below where work is being performed. A ½-inch (1.3-cm) wire rope or equivalent must be installed at a height of approximately 42 inches (106.7 cm) around the perimeter of temporary floors. Except when structural integrity is maintained by the design of the building, a permanent floor must be installed so that there are no more than eight stories between the erection floor and the highest permanent floor [25].

Demolition. Demolition should be performed by specialists who are familiar with relevant regulations and the procedures required to protect themselves, other workers, and the general public.

Electrical Hazards

This material is adapted from OSHA publication 3075, *Controlling Electrical Hazards* [26]. For further information, the reader is referred to this document and Code of Federal Regulations, 29 CFR 1910, Subpart S : Electrical.

Electricity is analogous to water flowing through a hose, where the power-generating station is the pump, the current (amperes) is the volume of water flowing, and the voltage (volts) is the pressure. The resistance to the flow of electricity is measured in ohms and is a function of the type, cross-sectional area, and temperature of the material subject to the current flow.

Electrical Shocks. Electricity must travel in a closed circuit through a material called a *conductor.* When the body is a part of this circuit, the electrical current passes through the body from one point to another, and a shock results.

The severity of the shock received by a person is generally a function of the amount of current flowing through the body, the path of the current between the points of contact of the body with the circuit, and the duration of the contact. Other factors that may affect the severity are the frequency (Hz) of the current, the phase of the heartbeat, and the general health of the individual. There are no absolute levels of current that cause the same sensation in all individuals. Figure 6.10.1 explains the general effect of a 60-cycle current lasting 1 second and passing from the hand to the foot (a common route). Note that current above the 5- to 30-milliampere range may cause the loss of muscle control and prevent the individual from voluntarily releasing the energized contact. This may cause a longer duration of exposure, resulting in severe injury or even death.

Injuries from Electrical Hazards. The most common injuries from electrical shock are burns. These may be electrical burns resulting from the electrical current passing through the body tissue, arc or flash burns resulting from the high temperatures produced by an electrical arc or explosion, thermal contact burns from skin coming into contact with the hot surfaces of overheated electrical conductors or energized equipment, or burns from ignited clothing. Electrical shock may also cause secondary injuries (sometimes called *body reaction injuries*) due to involuntary muscle reaction and falls. Injuries and property damage may also result from fires caused by electrical arcing or explosions.

Correcting Electrical Hazards. Electrical accidents are generally caused by unsafe equipment, unsafe environmental conditions, or unsafe work practices. Electrical hazards can be minimized through the use of insulation, guarding, grounding, mechanical safeguards, and safe employee work practices.

Current	Reaction
1 milliampere	Perception level. Just a faint tingle.
5 milliamperes	Slight shock felt; not painful but disturbing. Average individual can let go. However, strong involuntary reactions to shocks in this range can lead to injuries.
6–25 milliamperes (women); 9–30 milliamperes (men)	Painful shock, muscular control is lost. This is called the freezing current or "let-go"[*] range.
50–150 milliamperes	Extreme pain, respiratory arrest, severe muscular contractions.[*] Individual cannot let go. Death is possible.
1–4.3 amperes[†]	Ventricular fibrillation. (The rhythmic pumping action of the heart ceases.) Muscular contraction and nerve damage occur. Death is most likely.
10+ amperes	Cardiac arrest, severe burns, and probable death.

[*] If the extensor muscles are excited by the shock, the person may be thrown away from the circuit.

[†] Where shock durations involve longer exposure times (5 seconds or greater) and where only minimum threshold fibrillation currents are considered, theoretical values are often calculated to be as little as 1/10 the fibrillation values shown.

FIGURE 6.10.1 The effects of electrical current on the human body. (Reprinted from *Controlling Electrical Hazards,* OSHA Publication 3075, 1986.)

OCCUPATIONAL SAFETY MANAGEMENT AND ENGINEERING

Insulation involves the covering of electrical conductors (or potential conductors) with a material that has a very high resistance to electric current flow. Some good insulators are glass, mica, rubber, and plastic. OSHA's general requirements are that circuit conductors be insulated with a material suitable for the voltage and existing conditions (temperature, moisture, contaminants, etc.) to prevent accidental contact.

Indoor electrical installations of over 600 volts that are accessible to unqualified persons must be guarded by enclosing them in a lock-controlled area or in a metal case. Guarding live parts of 50 volts or more may be done in one of the following ways:

1. Location in a room or similar enclosure that is accessible only to qualified personnel
2. Installation of permanent, substantial screens or other partitions to exclude unqualified personnel
3. Location of the parts on a balcony, gallery, or platform elevated and configured to exclude unqualified personnel
4. Elevation of at least 8 feet (2.4 meters) above the floor

Grounding is normally a secondary measure that provides a low-resistance path to the earth or ground so that any excessive voltages will use this path and not the body as the route to complete the circuit. This reduces the possibility that an individual will be shocked through contact with improperly energized parts, such as the casing of an electrical hand tool. The *service ground,* or *system ground,* consists of one wire grounded at the transformer and at the service entrance of the building to prevent damage to machines, tools, and insulation. The *equipment ground* provides a path to ground from the specific tool or machine and protects the worker.

Mechanical safeguards automatically terminate or limit the electrical current when a ground fault, overload, or short circuit occurs. Fuses and circuit breakers monitor the amount of current in a circuit and open the circuit when the current flow is excessive. They serve primarily to prevent or reduce direct damage to conductors and equipment. They do little, however, to protect operators from direct shock hazards. Ground-fault circuit interrupters (GFCIs) are designed to terminate electrical power when there is a current loss (due to a short, for example) in the circuit that may be hazardous to operators. The GFCI senses when the current loss is as small as 0.005 ampere and terminates electrical power within as little as 0.025 second [27]. GFCIs are often used in high-hazard areas such as construction sites.

Employee safe work practices are required to minimize electrical hazards. They include the following:

1. De-energize electrical equipment before performing maintenance operations.
2. Use only electrical tools that are safe and properly maintained.
3. Use good judgment and follow applicable safety guidelines when working near energized lines.
4. Use adequate, properly maintained personal protective equipment.
5. Avoid, by at least 10 feet (3 meters), overhead power lines with ladders, cranes, or other equipment.

An excellent resource is *An Illustrated Guide for Electrical Safety,* available through the American Society of Safety Engineers [28].

Fires, Explosions, and Pressure

This material is adapted from *Accident Prevention Manual for Industrial Operations* [29] and *Occupational Safety Management and Engineering* [3]. For further information, the reader is referred to these documents and Code of Federal Regulations, 29 CFR 1910, Subpart L: Fire Protection.

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Fires. For a fire to start, there must be fuel, an oxidizer, heat, and a chemical chain reaction. The fuel and the oxidizer must be in proper proportions, and an uninhibited combustion chain reaction must occur.

Generally, fires pass through four stages. The *incipient stage* generates no visible smoke, flame, or significant heat but creates considerable combustion particles. Ionization fire detectors can be used to detect fires in this stage. As the amount of combustion particles increases and smoke is visible, the *smoldering stage* begins. Photoelectric fire detectors respond to this smoke. When the point of ignition is reached, the *flame stage* begins. The resulting infrared energy may be detected by infrared fire detectors. The flame stage usually becomes the *heat stage* very quickly. The resulting heat energy may be detected by thermal fire detectors.

Fires are generally divided into one of the following four classes according to the fuel involved:

Class A	Solids such as coal, paper, and wood that produce char or glowing embers.
Class B	Gasses and liquids that require vaporization for combustion.
Class C	Class A or B fires that involve electrical equipment.
Class D	Fires involving magnesium, aluminum, titanium, zirconium, or other easily oxidized metals.

The *flash point* of a liquid is that temperature at which it will give off sufficient vapor to momentarily ignite and burn. The burning stops as soon as the vapors are consumed. If the temperature rises above the *fire point,* the burning will continue after ignition. Liquids are often classified as *flammable* if their flash point is below a certain temperature or *combustible* if their flash point is above that temperature. The ratings for flammable and combustible are different for different organizations.

Fires can be extinguished by (1) removal or isolation of the fuel from the oxidizer (usually air), (2) increasing the volume of inert gas in the oxidizer, (3) quenching or cooling the heat of combustibles, or (4) inhibition of the combustion chain reaction. To extinguish fires, the proper type of extinguishing device must be used (based on the class and size of the fire). Only those trained in the use of fire-suppression equipment should attempt to fight fires. Improper use of such equipment could result in employee injury or an increase in the fire hazard. Hand fire extinguishers are effective only during the initial stages of a fire and therefore should be immediately accessible to trained personnel. According to Underwriters Laboratories the fire-fighting capacity of an extinguisher drops to 40 percent in the hands of an untrained user [30]. Therefore, it is important that all employees who are expected to operate fire extinguishers be trained in their proper use.

Explosions. An explosion is a sudden, violent release or expansion of a large amount of gas and can be caused by sudden release of compressed gas or by a chemical reaction. Explosions may cause damage and injuries through the resulting shock waves, material fragments, or body movement caused by the shock wave. Explosion damage may be prevented by (1) minimizing the use and storage requirements of explosive or pressurized materials, (2) isolating, with barriers or other protective features, potentially explosive materials and processes from people and valuable equipment, (3) use of pressure release devices, valves, or blowout panels, (4) use of suppressants that inhibit the chain reaction involved in chemical explosions, and (5) control and elimination of explosive dust concentrations.

Hand and Power Tools

This material is adapted from OSHA publication 3080, *Hand and Power Tools* [30]. For further information, the reader is referred to this document and Code of Federal Regulations, 29 CFR 1910, Subpart P: Hand and Portable Powered Tools and Other Hand-Held Equipment.

Hand Tools. Hand tools are nonpowered and include anything from hammers to screwdrivers. Hazards from hand tools often result from misuse and improper maintenance. Saw blades, knives, and other tools must be directed away from areas where other employees are working. Knives, scissors, and other cutting tools must be kept sharp, because dull tools are frequently more hazardous than sharp tools. Dull tools require more force and may be less predictable in their cutting action. Personal protective equipment such as mesh gloves, hand and arm guards, and protective aprons should be used when workers are using knives and other cutting tools. Spark-resistant tools should be used wherever sparks produced by iron or steel hand tools are a dangerous ignition source.

Power Tools. Power tools may use electric, pneumatic, liquid fuel, hydraulic, or powder activated. General power tool precautions include the following:

1. Never carry a tool by the cord or hose.
2. Never yank a cord or hose from the receptacle.
3. Keep cords and hoses away from heat, oil, and sharp edges.
4. Disconnect tools when servicing and changing accessories.
5. Keep bystanders at a safe distance.
6. Secure workpiece so two hands can use the tool.
7. Avoid accidental starting.
8. Maintain tools properly.
9. Maintain good footing and balance.
10. Do not wear loose clothing.
11. Properly tag damaged tools.

Hazardous Material

Hazardous materials are materials whose properties present health or safety hazards to workers, the facility, or the environment. Flammable, explosive, corrosive, extremely high or low temperature, toxic, and carcinogenic materials all present hazards beyond those associated with the handling of the materials themselves. The consequences of an accident involving hazardous materials are also more severe since they may result in a release and subsequent exposure of workers to the hazardous materials.

Approximately 32 million workers are potentially exposed annually to chemical hazards that may result in disorders such as heart ailments, kidney and lung damage, sterility, cancer, burns and rashes or may cause fires or explosions [31].

Special consideration must be given to operations that involve hazardous materials. Precautions may include preventive measures such as safe handling, spill prevention, the use of personal protective equipment and clothing, emergency showers and eyewash stations, and respiratory equipment. Preventive measures should also include substitution of less toxic or corrosive materials, isolation of the hazardous process by the use of enclosures, and provision of adequate exhaust ventilation.

Each container in the workplace must be tagged, labeled, or marked with the identity of hazardous material it contains. It must include prominently displayed warnings in written, picture, or symbol forms that convey the hazards of the chemical.

Chemical manufacturers and importers must develop Material Safety Data Sheets (MSDS) which include the name of the hazardous chemical, its specific chemical identity, physical and chemical characteristics, known acute and chronic health effects, exposure limits, precautionary measures, emergency and first-aid procedures, and the organization that prepared the MSDS. The MSDS for chemicals in a particular work area must be readily accessible to employees in that area during all work shifts. In addition, employers must establish a training and information program for all employees exposed to hazardous chemicals.

The environment in which the hazardous materials are stored, transported, and processed often must be controlled. For example, some locations where flammable materials are stored, handled, or used may require the use of explosion-proof, intrinsically safe, or otherwise protected equipment depending on the fire risks (classification) of the that area [32].

For further information, the reader is referred to OSHA publication 3084, *Chemical Hazard Communication* [31] and Code of Federal Regulations, 29 CFR 1910, Subpart H: Hazardous Materials [33].

Machine Guarding

This material is adapted from OSHA publication 3067, *Concepts and Techniques of Machine Safeguarding* [34]. For further information, the reader is referred to this document and Code of Federal Regulations, 29 CFR 1910, Subpart O: Machinery and Machine Guarding.

Guarding is required at the point of operation where work is performed on the material (cutting, shaping, forming, etc.), around power transmission apparatus, and around other moving parts. Hazardous motions include rotating, reciprocating, and transverse actions. Hazardous actions include cutting, punching, shearing, and bending.

Guarding mechanisms must, at a minimum, (1) prevent contact between the worker and dangerous moving parts, (2) be firmly attached to the machine and discourage tampering, (3) protect from inadvertent insertion or dropping of foreign objects, (4) create no new hazards, (5) create minimum interference with job performance, and (6) allow safe maintenance.

Machine guarding may be grouped into five general classifications: (1) guards, (2) devices, (3) location and distance, (4) feeding and ejection mechanisms, and (5) miscellaneous aids.

Guards. Guards may be fixed, interlocked, adjustable or self-adjusting. A *fixed* guard is a permanent part of the machine and generally encloses the entire point of operation. A fixed guard is often preferred because of its simplicity. Care must be taken, however, to allow safe access for inspection and maintenance. When an *interlocked* guard is opened or removed the machine automatically shuts off or cannot cycle until the guard is replaced. *Adjustable* guards accommodate parts of different sizes or shapes. *Self-adjusting* guards adjust automatically to the movement of the stock or part being inserted.

Devices. Devices may be presence-sensing, pullback, restraint, safety controls, or gates. *Presence-sensing devices* detect the presence of a foreign object (hand, for example) in the operating area and interrupt the operating cycle. Presence-sensing devices are generally photoelectric, radiofrequency, or electromechanical. Presence-sensing devices must be fail-safe so that a failure within the detection system prevents operation of the machine [35]. *Pullback devices* include attachments to the operator's hands, wrists, or arms that withdraw the body member from the point of operation when the machine cycles. *Restraint devices* also include attachments, usually to the wrists, that keep the operator's hands away from the point of operation altogether. *Safety controls* may be of several types. Safety trip controls (bars, trip wires, triprods) provide a quick means to stop the machine in an emergency situation. Two-hand controls require the concurrent use of both hands to cycle the machine, and a two-hand trip requires the concurrent use of two hands to start the machine. A *gate* is a movable barrier that must be in place at the point of operation before the machine cycle can start.

Location/Distance. The dangerous parts of the machine must be located so that they are not accessible or do not present a hazard to the operator during normal operation. Workers may be protected by a wall, or dangerous parts may be located high enough to be out of any possible reach. Operator controls may be located at a safe distance from the machine if the operator is not required to tend the process.

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Feeding/Ejection Mechanisms. Feeding and ejection mechanisms may protect the operator by eliminating the need for the operator to place his or her hands in the point of operation. Guards and devices may still be required to protect the operator.

Miscellaneous Aids. These include awareness barriers that remind workers of dangers or dangerous areas, protective shields, and tools that may be used to insert and remove stock from the point of operation.

Figure 6.10.2 is a checklist to remind the reader of important machine-guarding issues.

Material Handling and Storage

Whether the material is moved manually or with the assistance of mechanized equipment, material handling can result in injuries, property damage, or loss of product. The mishandling of materials is considered the single largest cause of accidents and injuries in the workplace [36]. Materials handling is estimated to account (at least in part) for 20 to 45 percent of all occupational accidents [37]. The best method for increasing the safety in materials handling is to reduce or eliminate it altogether. In other words, the less materials must be handled, the safer and more efficient the operation. In the initial design or redesign of facilities, the objective is to eliminate unnecessary manual or mechanical handling of materials. Ideally, this is done when the facility layout and equipment are designed. For example, designs should place receiving areas for raw materials as close as possible to the machinery that will use those materials. When the handling of materials cannot be eliminated altogether, an alternative is to use mechanical equipment in place of manual handling. Material handling represents an area where major waste, loss of resources, and loss of productivity can occur and where management can effect major improvements in both productivity and profitability by reducing or eliminating accident-causing hazards.

Moving by Hand. Sometimes, manual handling and lifting of materials is necessary, and ergonomic principles must be employed to ensure that the manual handling is performed as safely as possible. The consideration of ergonomics in the design of manual material-handling tasks can result in reduced physical stress and lower injury costs. The weight of the load and the bending, twisting, and turning of the body are often associated with injury during manual material handling. Injuries include (1) musculoskeletal strains and sprains from lifting or moving loads that are too heavy or too large, (2) fractures and bruises caused by dropped or moving material or getting caught in pinch points, and (3) cuts and bruises caused by dislodgment of improperly stored material or incorrect cutting of ties or other securing devices.

The following general guidelines minimize the musculoskeletal hazards associated with manual material handling:

1. Keep the load close to the body.
2. Use the most comfortable posture.
3. Do not twist while lifting or lowering the load.
4. Lift slowly and evenly (don't jerk the load).
5. Securely grip the load.
6. Use a lifting aid or get help.

Refer to the *Applications Manual for the Revised NIOSH Lifting Equation* [38] for additional information on the analysis of manual material-handling tasks.

Moving by Machine. When a powered industrial forklift is used to move material, the load must be squarely centered on the forks as close to the mast as possible. The lift truck must never be overloaded. Stacked loads must be correctly piled and cross-tiered whenever possible.

Machine Guarding Checklist

Answers to the following questions should help the interested reader determine the safeguarding needs of his or her own workplace, by drawing attention to hazardous conditions or practices requiring correction.

Requirements for all safeguards	Yes	No
1. Do the safeguards provided meet the minimum OSHA requirements?	______	______
2. Do the safeguards prevent workers' hands, arms, and other body parts from making contact with dangerous moving parts?	______	______
3. Are the safeguards firmly secured and not easily removable?	______	______
4. Do the safeguards ensure that no objects will fall into the moving parts?	______	______
5. Do the safeguards permit safe, comfortable, and relatively easy operation of the machine?	______	______
6. Can the machine be oiled without removing the safeguard?	______	______
7. Is there a system for shutting down the machinery before safeguards are removed?	______	______
8. Can the existing safeguards be improved?	______	______

Mechanical hazards		
The point of operation:		
1. Is there a point-of-operation safeguard provided for the machine?	______	______
2. Does it keep the operator's hands, fingers, body out of the danger area?	______	______
3. Is there evidence that the safeguards have been tampered with or removed?	______	______
4. Could you suggest a more practical, effective safeguard?	______	______
5. Could changes be made on the machine to eliminate the point-of-operation hazard entirely?	______	______
Power transmission apparatus:		
1. Are there any unguarded gears, sprockets, pulleys, or flywheels on the apparatus?	______	______
2. Are there any exposed belts or chain drives?	______	______
3. Are there any exposed set screws, key ways, collars, etc.?	______	______
4. Are starting and stopping controls within easy reach of the operator?	______	______
5. If there is more than one operator, are separate controls provided?	______	______
Other moving parts:		
1. Are safeguards provided for all hazardous moving parts of the machine including auxiliary parts?	______	______

Nonmechanical hazards		
1. Have appropriate measures been taken to safeguard workers against noise hazards?	______	______
2. Have special guards, enclosures, or personal protective equipment been provided, where necessary, to protect workers from exposure to harmful substances used in machine operation?	______	______

Electric hazards		
1. Is the machine installed in accordance with National Fire Protection Association and National Electrical Code requirements?	______	______
2. Are there loose conduit fittings?	______	______
3. Is the machine properly grounded?	______	______
4. Is the power supply correctly fused and protected?	______	______
5. Do workers occasionally receive minor shocks while operating any of the machines?	______	______

Training		
1. Do operators and maintenance workers have the necessary training in how to use the safeguards and why?	______	______
2. Have operators and maintenance workers been trained in where the safeguards are located, how they provide protection, and what hazards they protect against?	______	______

FIGURE 6.10.2 Important machine guarding issues. (Reprinted from *Concepts and Techniques of Machine Safeguarding,* OSHA Publication 3067, 1992.)

Training (*Continued*)	Yes	No
3. Have operators and maintenance workers been trained in how and under what circumstances guards can be removed?	______	______
4. Have workers been trained in the procedures to follow if they notice guards that are damaged, missing, or inadequate?	______	______

Protective equipment and proper clothing		
1. Is protective equipment required?	______	______
2. If protective equipment is required, is it appropriate for the job, in good condition, kept clean and sanitary, and stored carefully when not in use?	______	______
3. Is the operator dressed safety for the job (i.e., no loose-fitting clothing or jewelry)?	______	______

Machinery maintenance and repair		
1. Have maintenance workers received up-to-date instruction on the machines they service?	______	______
2. Do maintenance workers lock out the machine from its power sources before beginning repairs?	______	______
3. Where several maintenance persons work on the same machine, are multiple lockout devices used?	______	______
4. Do maintenance persons use appropriate and safe equipment in their repair work?	______	______
5. Is the maintenance equipment itself properly guarded?	______	______
6. Are maintenance and servicing workers trained in the requirements of 29 CFR 1910.147, lockout/tagout hazard, and do the procedures for lockout/tagout exist before they attempt their tasks?	______	______

FIGURE 6.10.2 (*Continued*) Important machine guarding issues. (Reprinted from *Concepts and Techniques of Machine Safeguarding,* OSHA Publication 3067, 1992.)

Drivers of industrial forklifts must be trained in the safe operation of lift trucks, including the specific operating controls and hazards associated with the make and model of truck they are using [39].

Hazards associated with conveyors include pinch points between moving conveyor components or items moving on the conveyor and stationary portions of the conveyor, pinch points caused by items jamming up against one another on the conveyor, objects falling from the conveyor, conveyor components themselves falling, workers falling from conveyors they attempt to cross or ride, workers bumping into conveyor components, accidental starting during maintenance or troubleshooting, and contact with power transmission components such as belts, chains, gears, or pulleys [40].

The most severe conveyor accidents occur when the conveyor is accidentally restarted during maintenance or servicing. Typically, the employee conducting the repairs is in a vulnerable position in close proximity with power transmission apparatus and moving parts from which the guards have been removed. For this reason, strict adherence to the OSHA Lockout/Tagout standard is critical [41]. Conveyors must be equipped with emergency stop devices. Nip points and other hazards must be guarded, and guards must be provided wherever a conveyor passes over work areas or aisles.

When stacking material, height and weight limitations, accessibility, and material stability must be considered. All materials stored in tiers should be placed on racks, interlocked, or secured in some way to prevent falling or collapse. Flammable or combustible liquid, liquefied petroleum gas, explosives and blasting agents, and other hazardous materials must be stored in accordance with applicable safety and health regulations.

Sufficient clearance must be provided at aisles, loading docks, doorways, areas where turns are required, or other locations where the movement of material by machines might present a hazard. Permanent aisles and storage locations should be marked.

Storage. The storage of materials may interfere with plant operations, impede emergency exit, or present a hazard itself. Sharp or protruding edges, flammable or combustible materials, unstable or shifting materials, and material stored in passageways all present hazards. Materials should not block access to machinery controls or safety equipment such as fire extinguishers, eyewash stations, fire alarms, or first-aid kits. If it is important that the first materials placed into storage be the first removed and used (first-in, first-out method), then the storage method should allow for this without requiring additional handling.

Storage space at most manufacturing facilities is a precious commodity and cannot be wasted or inefficiently used. Inventory, whether raw materials, work-in-progress, or finished product, always costs money. The just-in-time (JIT) production method seeks to eliminate inventory of materials altogether. In a JIT system, raw materials and supplies are received just in time to be processed. Subassemblies are produced from these supplies just in time for incorporation into finished products, and these finished products are delivered just in time to customers. JIT reduces the need to handle parts to and from storage. The cost savings associated with reductions in storage space, material handling, and human resources are the most obvious benefits of JIT manufacturing, but the reduction in material handling can also greatly improve the safety of an operation. Quality and efficiency are also increased because production problems become immediately evident, and scrap is reduced because bad components are not assembled and stockpiled [42].

Storage facilities should be clean, orderly, and secure in order to conserve space and minimize hazards. Consideration should be given to the materials being stored, their proximity to other materials and processes, the storage methods to be employed (racks, pallets, bins, tanks, etc.), and paths to exits. Management should recognize that good housekeeping is critical to safe storage. Rubbish, trash, and other waste should be disposed of at regular intervals to prevent fire and tripping hazards.

Materials stacked too closely to sprinklers can block the flow of water and limit effectiveness. Typically, a minimum of at least 18 inches (45.7 cm) of clearance is needed. Depending on the class, quantity, and height of rack storage, in-rack sprinklers may also be necessary [43]. Exits and paths to exits must be clearly marked and free of obstructions and other hazards.

Storage racks should be securely bolted or fastened to the floor and walls to prevent tipping. These fastenings should be inspected periodically, particularly where they may be damaged by forklifts. Where materials are stacked, provisions should be made to ensure secure, stable piles. For example, bags or sacks should be interlocked to stabilize the load. Markings may be provided to indicate the maximum height at which materials can be stacked to prevent the floor or rack load limit from being exceeded and maintain proper clearance from sprinklers. Employees should be forbidden from climbing on storage racks to retrieve or store items.

Where mechanical materials-handling equipment is used, designating separate pedestrian and vehicle paths is recommended. Ideally, pedestrian paths should be separated from vehicular traffic by physical barriers such as chains or guardrails.

Employees should travel through doorways provided for pedestrian use, not bay or dock doors used by forklifts and other handling equipment. A quick move by a pedestrian into the vehicular aisle may not allow enough time for the equipment operator to stop. Also, the visibility of both the pedestrian and the equipment operator may be impaired by changes in lighting or by flexible doors (such as overlapping plastic slats). Vehicle operators should slow, stop, and sound their horns as they enter doorways, intersections, or other limited-visibility areas.

Aisles and passageways must always be kept clear of obstructions and tripping hazards. Materials in excess of what is needed for the immediate operations should not be stored in work areas or paths to and from work areas.

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Housekeeping. Poor housekeeping is often indicative of poor safety practices. Good housekeeping will help make unsafe conditions more obvious and provide an atmosphere more conducive to safe behavior.

Material Flow. By analyzing the flow of materials, the industrial engineer can identify and correct hazardous or potentially hazardous operations and locations.

In order to determine which materials-handling processes can be modified or eliminated, it is necessary to understand the materials flow requirements. A thorough understanding of how materials must be processed, combined, and moved to produce a product is essential for eliminating unnecessary handling. In many cases, the process bottlenecks are also the biggest safety concerns. Eliminating these bottlenecks during the design phase makes the operation both safer and more productive.

Machine locations within a plant are typically fixed and cannot be altered significantly after installation, and maximal optimization may not be achievable with alteration of paths and routes alone. Flowcharts, flow diagrams, simulation, and similar techniques for displaying and analyzing information graphically can be helpful in planning or revising material flow patterns. There are several techniques available for determining potential hazards, including the job safety analysis (JSA) discussed later in this chapter.

An analysis of material movement patterns provides the information necessary to determine transport methods, routes, and aisles so the number of turns, blind corners, and crossing routes can be minimized or planned for. Considerations include the locations of warning signs or parabolic mirrors for increased visibility, physical barriers between pedestrians and equipment, one-way traffic zones, and training for both equipment operators and pedestrians.

The first goal of material flow analysis should be to eliminate unnecessary handling. The next challenge is to mechanize as much of the handling as possible. Priority should be given to those strenuous tasks that present the biggest ergonomic risk to workers. When feasible, the mechanization should involve full automation or should be controlled by the operator without requiring direct manual handling.

For further information, refer to OSHA publication 2236, *Materials Handling and Storage* [44] and Code of Federal Regulations, 29 CFR 1910, Subpart N: Materials Handling and Storage.

Noise

Noise may be defined as unwanted sound. Excessive noise may result in (1) decreased hearing sensitivity, (2) immediate physical damage, (3) interference or masking of particular sounds, (4) annoyance, (5) distraction, and (6) contribution to other types of disorders [3].

The reduction of the adverse effects of noise in the workplace may be accomplished through (1) early planning, (2) reduction of noise at its source, (3) insulation against reflected noise, and (4) use of personal protective equipment (PPE). The implementation of early planning to reduce the potential for noise exposure is the preferred option. Reduction of noise at the source and insulation can be very costly, and the use of PPE may be difficult and cause worker discomfort and is not always effective, particularly if not properly used.

OSHA requires that employers monitor noise exposure levels to identify employees who are exposed to noise at or above 85 dB(A) averaged over an 8-hour day (time-weighted average or TWA). A time-weighted average (TWA) is simply the average sound level for a given period of time weighted by the fraction of time spent at each sound level. Hearing protection must be available to employees who are exposed to an 8-hour TWA of 85 dB(A) or above, and hearing protection must be worn by employees who are exposed to an 8-hour TWA of 90 dB(A) or above. The hearing protection must attenuate employee exposure to an 8-hour TWA of 90 dB(A).

Personal Protective Equipment

This material is adapted from OSHA Fact Sheet No. 86-08, *Protect Yourself with Personal Protective Equipment* [45]. For further information, refer to this document and Code of Federal Regulations, 29 CFR 1910, Subpart I: Personal Protective Equipment.

OSHA requires that employers assess the workplace to determine whether hazards are present or likely to be present that would necessitate the use of personal protective equipment (PPE) [46]. If such hazards are present, the employer must select and enforce the use of PPE that will protect workers from those hazards. The employer must verify with a written certification that the workplace has been evaluated and that necessary PPE has been selected. Workers must be trained in its proper use and care.

OSHA standards require employers to furnish personal protective equipment (PPE) and require employees to use this equipment when there is a "reasonable probability" that the use of such equipment will prevent injury. Data from the Bureau of Labor Statistics indicates that 60 percent of workers with eye injuries were not wearing eye protection, 99 percent of workers suffering face injuries were not wearing face protection, 84 percent of workers sustaining head injuries were not wearing hard hats, and 77 percent of workers incurring foot injuries were not wearing safety shoes.

The type of eye and face protection should be based on the type of hazard present and the degree of exposure. Selection criteria include comfort, snugness of fit, durability, and maintainability. Head protection must be able to resist penetration and absorb the shock associated with a blow to the head. Some situations also call for protection against electric shock. Foot and leg protection is required to protect against falling or rolling material, sharp objects, molten metal, and hot, wet, and slippery surfaces. Safety shoes must be sturdy and have an impact-resistant toe.

Hearing-conservation programs require the use of hearing protectors in some cases. Hearing protectors may be preformed or molded (which are fitted to the individual) or waxed cotton, foam, or fiberglass (which are self-forming). Disposable earplugs should be worn once and discarded, and nondisposable earplugs should be properly maintained. A variety of PPE is available to protect the arms, hands, and torso from cuts, heat, splashes, impact, acids, and radiation. This equipment must be selected to fit the particular task. Respiratory protection is required when there is exposure to air contaminated with hazardous dusts, fogs, fumes, mists, gases, smokes, sprays, or vapors in excess of the OSHA Permissible Exposure Limits (PELs) for those materials. Where atmospheric contamination cannot be prevented and respirators are used to control exposures, a respirator program must be in place. A respirator program outlines requirements for selection, use, fitting, inspection, and user medical status (fitness to wear a respirator) [47].

Employees must be trained in the proper use and maintenance of PPE. They must also be aware that the use of the PPE does not eliminate the hazard. If the PPE fails, harmful exposure may result.

Radiation

Radiation is energy transmitted through space. Ionizing radiation (x-rays, gamma rays, cosmic rays, for example) changes atoms into ions through the addition or removal of electrons. A radioactive material is generally considered to be a substance that emits ionizing radiation. Adverse effects of exposure to excessive radiation include cancer, birth defects in future children of exposed parents, and cataracts. There is no conclusive evidence of a cause-effect relationship between adverse health effects and current levels of occupational radiation exposure. It is advisable, however, to assume that some health effects may occur at some occupational exposure levels. In addition, the Nuclear Regulatory Commission requires that exposures to workers and the public be kept as low as reasonably achievable (ALARA) [48]. The hazard associated with exposure to ionizing radiation can be reduced through the reduction of exposure time, increase in distance between the worker and the radiation source, and appropriate shielding between the worker and the radiation source.

Nonionizing radiation such as ultraviolet, visible light, infrared, microwave, and lasers may also be hazardous. The risks from these sources can be reduced through the use of appropriate glasses, skin creams, clothing, gloves, and face masks, in addition to the time, distance, and shielding measures already noted.

Robot Safety

This material is adapted from *NIOSH Alert—Request for Assistance in Preventing the Injury of Workers by Robots* [49]. For further information, refer to this document and *Safe Maintenance Guide for Robotic Workstations* [50].

While workers may recognize the hazards associated with the working end of the robot arm, they may not recognize the dangers associated with robot maintenance or the movement of other parts of the robot. The safety of robotic systems must consider the actual design of the robot, worker training, and worker supervision.

1. *Robot design.* Robot design should include the following:

   Physical barriers with interlocked gates

   Motion sensors, light curtains, or floor sensors that stop the robot when a worker crosses the barrier

   Barriers between robotic equipment and freestanding objects to eliminate pinch points

   Adequate clearance around all moving components

   Remote diagnostic instrumentation to facilitate troubleshooting away from the moving robot

   Adequate illumination of control and operational areas

   Marks on the floor and working surfaces to indicate the movement area of the robot (work envelope)

2. *Worker training.* Training of operators and maintenance personnel should include the following:

   Familiarity with all working aspects of the robot, including range of motion, known hazards, programming, emergency stop methods, and safety barriers

   Importance of staying out of the reach of the robot during operation

   Necessity of operating at reduced speed and awareness of all pinch points during programming

3. *Worker supervision.* Supervisors of operators and maintenance personnel have the following responsibilities:

   To ensure that no one is allowed within the operational area of the robot without first shutting down or reducing the speed of the robot

   To recognize that, over time, workers may become complacent or inattentive to the hazards inherent in robotic equipment

In addition to robots, many facilities are incorporating other types of automation. Automated guided vehicles (AGVs) and automated storage/retrieval systems (AS/RSs) are becoming increasingly common. Because they lack direct human control or supervision, they may introduce new safety concerns into the work environment.

An *automated guided vehicle* (AGV) is a material transport vehicle that travels over prearranged routes with movement controlled by electromagnetic wires buried in the floor, optical guidance, infrared, inertial guidance (gyroscope), position-referencing beacons, or computer programming [51].

AGVs must be equipped with a means for stopping if someone or something is in the path. This is usually achieved via a lightweight, flexible bumper that shuts off power and applies the brakes when contacted [39]. AGV bumpers should not need hardware or software logic or signal conditioning in order to operate. Also, AGVs in automatic mode must stop immediately when they lose guidance [51]. Most vehicles are programmed to require manual reset before resuming motion [52].

Blinking or rotating lights and/or warning bells can alert workers to the presence of AGVs in their work area, and turn signals can alert pedestrians to which way an AGV will be turning. AGVs must have clearly marked and unobstructed aisles for operation [39].

An *automated storage/retrieval system* (AS/RS) is defined by the Materials Handling Institute as "a combination of equipment and controls which handles, stores, and retrieves materials with precision, accuracy, and speed under a defined degree of automation" [53]. Typically, these systems consist of a series of storage aisles with one or more storage/retrieval (S/R) machines, usually one per aisle, used to deliver materials. AS/RSs are not directly controlled by operators and therefore require that access to the storage areas be interlocked or otherwise guarded to protect workers from the moving equipment. More information on AS/RS machines can be found in the ASME B30.13 Standard "Storage/Retrieval (S/R) Machines and Associated Equipment" [54].

Slips and Falls

Slips and falls may be from an elevation or on the same level. Slips and falls from elevations were mentioned in the earlier discussion of construction safety. Falls on the same level tend to result from either a stumble, which is the contact of a foot or leg with an unexpected obstruction, or an actual slip between the shoe and walking surface.

Stumbles can best be prevented by good housekeeping, proper illumination and marking of walkways, and load-carrying techniques that do not overload or affect the visibility of workers. Slips can be prevented by proper maintenance of the work surface and the selection of footwear that optimizes the slip resistance between the footwear and the walking surface. While some standards suggest that adequate slip resistance in the workplace is defined by a coefficient of friction of 0.5, there is some lack of agreement regarding how this slip resistance is to be measured. In some cases, such as walking on ramps or pushing and pulling heavy loads, a higher slip resistance may be required. Emphasis should be placed on the maximization of slip resistance under all expected operational conditions through the selection of optimum shoe and floor-surface materials.

SYSTEMS SAFETY ANALYSIS

The general area of *system safety analysis* may be defined as a directed or systematic process for the acquisition, review, and analysis of specific information relevant to a particular system. This process is methodical, careful, and purposeful. The purpose is to provide information for informed management decisions. System safety analysis techniques can be categorized as either inductive or deductive [2].

Inductive Methods of Systems Safety Analysis

Inductive methods use observable data to predict what *can* happen. These techniques consider systems from the standpoint of the component parts and determine how a particular mode of failure of component parts will affect the performance of the system. Major inductive methods are *preliminary hazard analysis* (PHA), *job safety analysis* (JSA), *failure modes and effects analysis* (FMEA), and *systems hazard analysis* (SHA).

Preliminary Hazard Analysis (PHA). Preliminary hazard analysis is a qualitative study conducted during the conceptual or early developmental phases of a system's life. Its objectives are as follows:

1. Identify known hazardous conditions and potential failures.
2. Determine the cause(s) of these conditions and potential failures.
3. Determine the potential effect of these conditions and potential failures on personnel, equipment, facilities, and operations.
4. Establish initial design and procedural requirements to eliminate or control these hazardous conditions and potential failures.

In some cases an additional step, the estimation of the probability of an accident due to the hazard, is performed between steps 3 and 4.

Figure 6.10.3 presents an amusing but illustrative PHA of the feathers, flax, and beeswax wings used by Daedalus and Icarus in Greek mythology [3].

The PHA is often based on a limited number of hazards, which are determined as soon as initial facts about the system are known. These basic hazards must be dealt with even though there are many different circumstances that might lead to them. The design process may be monitored to determine whether these hazards have been reduced or eliminated and, if not, whether the effects can be controlled.

Job Safety Analysis (JSA). Job safety analysis is a written procedure designed to review job methods, uncover hazards, and recommend safe job procedures. Smith [55] notes the following four basic steps in making a JSA:

1. Select the job, usually basing selection on potential hazards or high incidence rates.
2. Break the job down into a sequence of steps. Job steps are recorded in their normal order of occurrence. Steps are described in terms of *what* is done ("lift," "attach," "remove"), not *how* it is done.
3. Identify the potential hazards. To determine what accidents can happen, one should: (1) observe the job, (2) discuss the job with the operator, and (3) check accident records.
4. Recommend safe job procedures to avoid the potential accident.

A basic JSA form should include the job steps, the hazards associated with these steps, and recommended safe procedures, but the form may be altered to meet specific organizational needs by including such information as the name of the person performing the analysis, names of the operator and supervisor, and names of reviewers or approvers of the analysis.

Failure Modes and Effects Analysis (FMEA). Failure modes and effects analysis has two functions: to analyze system safety and reliability to identify the critical failure modes that seriously affect the safe and successful life of the system and (2) to analyze failure modes that could prevent a system from accomplishing its intended mission. This technique permits system change in order to reduce the severity of failure effects. FMEA is organized around what-if questions. The areas that are covered and the questions that are asked move logically from cause to effect.

1. *Component.* What individual components make up the system?
2. *Failure modes.* What could go wrong with each component in the system?
3. *System causes.* What would be the cause of the component failure or malfunction?
4. *System effects.* What would be the effect of such a failure on the system, and how would this failure affect other components in the system?
5. *Severity index.* Consequences are often placed into one of four severity categories ranging from catastrophic (category I) to negligible (category IV) [4].
   a. Catastrophic (category I): May cause multiple injuries, fatalities, or loss of a facility.
   b. Critical (category II): May cause severe injury, severe occupational illness, or major property damage.

Preliminary Hazard Analysis

Identification: Mark I Flight System Subsystem: Wings Designer: Daedalus

Hazard	Cause	Effect	Probability of accident due to hazard	Corrective or preventive measure
Thermal radiation from sun	Flying too high in presence of strong solar radiation	Heat may melt beeswax holding feathers together. Separation and loss of feathers will cause loss of aerodynamic lift. Aeronaut may then plunge to his death in the sea.	Reasonably probable	Make flight at night or at time of day when sun is not very high and hot. Provide warning against flying too high and too close to sun. Maintain close supervision over aeronauts. Use buddy system. Provide leash of flax between the two aeronauts to prevent young, impetuous one from flying too high. Restrict area of aerodynamic surface to prevent flying too high.
Moisture	Flying too close to water surface or from rain	Feathers may absorb moisture, causing them to increase in weight and to flag. Limited propulsive power may not be adequate to compensate for increased weight so that the aeronaut will gradually sink into the sea. Result: loss of function and flight system. Possible drowning of aeronaut if survival gear is not provided.	Reasonably probable	Caution aeronaut to fly through middle air where sun will keep wings dry or where accumulation rate of moisture is acceptable for time of mission.
Inflight encounter	a. Collision with bird	Injury to aeronaut	Remote probability	a. Select flight time when bird activity is low. Give birds right-of-way.
	b. Attack by vicious bird	Injury to aeronaut	Remote probability	b. Avoid areas inhabited by vicious birds. Carry weapon for defense.
Hit by lightning bolt	Bolt thrown by Zeus angered by hubris displayed by aeronaut who can fly.	Death of aeronaut	Happens occasionally	Aeronaut should not show excessive pride in being able to perform godlike activity (keep a low profile).

FIGURE 6.10.3 Preliminary hazard analysis of flight of Daedalus and Icarus. (Reprinted with permission from Hammer, W., *Occupational Safety Management and Engineering, 4th ed.,* Prentice-Hall, Englewood Cliffs, New Jersey, 1989, p. 553.)

c. Marginal (category III): May cause minor injury or minor occupational illness resulting in lost workday(s), or minor property damage.

d. Negligible (category IV): Probably would not affect the safety or health of personnel but is still in violation of a safety or health standard.

6. *Probability index.* How likely is the event to occur under the circumstances described and given the required precursor events? These probabilities are based on such factors as accident experience, test results from component manufacturers, comparison with similar equipment, or engineering data. Probability categories may be developed by individual companies or analysts but are sometimes classified as [4]:

a. Probable (likely to occur immediately or within a short period of time)

b. Reasonably probable (probably will occur in time)

c. Remote (possible to occur in time)

d. Extremely remote (unlikely to occur)

7. *Action or modification.* After the failure modes, causes and effects, severity, and probability have been established, it is necessary to modify the system to prevent or control the failure.

Firenze [4] notes that the severity index, the probability index, and a third index relating to personnel exposure may be used to determine the overall risk. A review of the preceding steps makes the objectives of FMEA clear. FMEA is intended to rank failures by risk (severity and probability) so that potentially serious hazards can be corrected.

When the analysis includes the severity, probability, and criticality indexes, it is sometimes called a *failure modes, effects, and criticality analysis* (FMECA).

Systems Hazards Analysis (SHA). Systems hazards analysis includes the human component, a strength of job safety analysis, and the hardware component, a strength of failure modes and effects analysis [56].

SHA concentrates on the worker-machine interface. What process is being performed on what equipment? What major operations are required to complete the process? What tasks or activities are required to complete an operation? The thesis of SHA is that failures (undesired events) may be eliminated by systematically tracking through the system to look for hazards that may result in a failure situation.

In the language of SHA, the terms *process, operation,* and *task* have specific meanings. *Process* is the combination of operations and tasks that unite physical effort and physical and human resources to accomplish a specific purpose. An *operation* is a major step in the overall process (for example, drilling and countersinking stock on a drill press). A *task* is a particular action required to complete the operation (for example, placing a cutting tool in a holder prior to sharpening the tool on the grinder).

Once the process to be analyzed has been identified, it is broken down into its operations and tasks. To do this, the analyst must be familiar with the tasks involved in the operation and the interactions between and within the system being analyzed and associated systems and subsystems. Often, a flow diagram is constructed to record what is taking place throughout the flow of operations and tasks that fulfill process demands. This enables the analyst to see the pertinent subsystems, methods, transfer operations, inspection techniques, and human-machine operations.

Deductive Methods of Systems Safety Analysis

Inductive methods of analysis analyze the components of the system and consider the effects of their failure on total system performance. Deductive methods of analysis move from the end event to try to determine the possible causes. They determine how a given end event *could* happen [56]. One widespread application of deductive systems safety analysis is Fault Tree Analysis.

Fault Tree Analysis (FTA). Fault tree analysis postulates the possible failure of a system and then identifies component states that contribute to the failure, reasoning backward from the undesired event to identify all the ways in which such an event could occur and, consequently, the contributory causes. The lowest levels of a fault tree involve individual components or processes and their failure modes. This level of the analysis generally corresponds to the starting point of FMEA.

FTA uses Boolean logic and algebra to represent and quantify the interactions between events. The primary Boolean operators are AND and OR gates. With an AND gate, the output of the gate, the event that is at the top of the symbol, occurs only if *all* of the conditions below the gate and feeding into the gate coexist. With the OR gate, the output event occurs if *any one* of the input events occur. Figure 6.10.4 [3], illustrates the basic gates used and a simple FTA.

When the probabilities of initial events or conditions are known, it is possible to determine the probabilities of succeeding events through the application of Boolean algebra. For an AND gate, the probability of the output event is the intersection of the Boolean probabilities, or the product of the probabilities of the input events:

$$\text{Probability (output)} = (\text{prob input } 1) \times (\text{prob input } 2) \times (\text{prob input } 3)$$

For an OR gate, the probability of the output event is the probability that any of the input events will happen, or the sum of the probabilities of the input events minus the redundant intersections, which indicate where the input events can happen simultaneously. This calculation is tedious and can be replaced by 1 minus the probability that none of the input events will happen:

$$\text{Probability (output)} = 1 - [1 - (\text{prob input } 1)][1 - (\text{prob input } 2)][1 - (\text{prob input } 3)]$$

Management Oversight and Risk Tree Analysis (MORT). *Management oversight and risk tree analysis,* similar to FTA, is defined as follows:

> A formalized, disciplined logic or decision tree to relate and integrate a wide variety of safety concepts systematically. As an accident analysis technique, it focuses on three main concerns: specific oversights and omissions, assumed risks, and general management system weaknesses [57].

It is essentially a series of fault trees with three basic subsets or branches:

1. A branch that deals with specific oversights and omissions at the worksite.
2. A branch that deals with the management system that establishes policies and makes them work.
3. An assumed risk branch that acknowledges that no activity is completely free of risk and that risk management functions must exist in any well-managed organization. These assumed risks are those undesirable consequences that have been quantitatively analyzed and formally accepted by appropriate management levels within the organization.

MORT includes about 100 generic causes and thousands of criteria. The MORT diagram terminates in some 1500 basic safety program elements that are required for a successfully functioning safety program. These elements prevent the undesirable consequences indicated at the top of the tree. MORT has three primary goals:

1. To reduce safety-related oversights, errors, and omissions
2. To allow risk quantification and the referral of residual risk to proper organizational management levels for appropriate action

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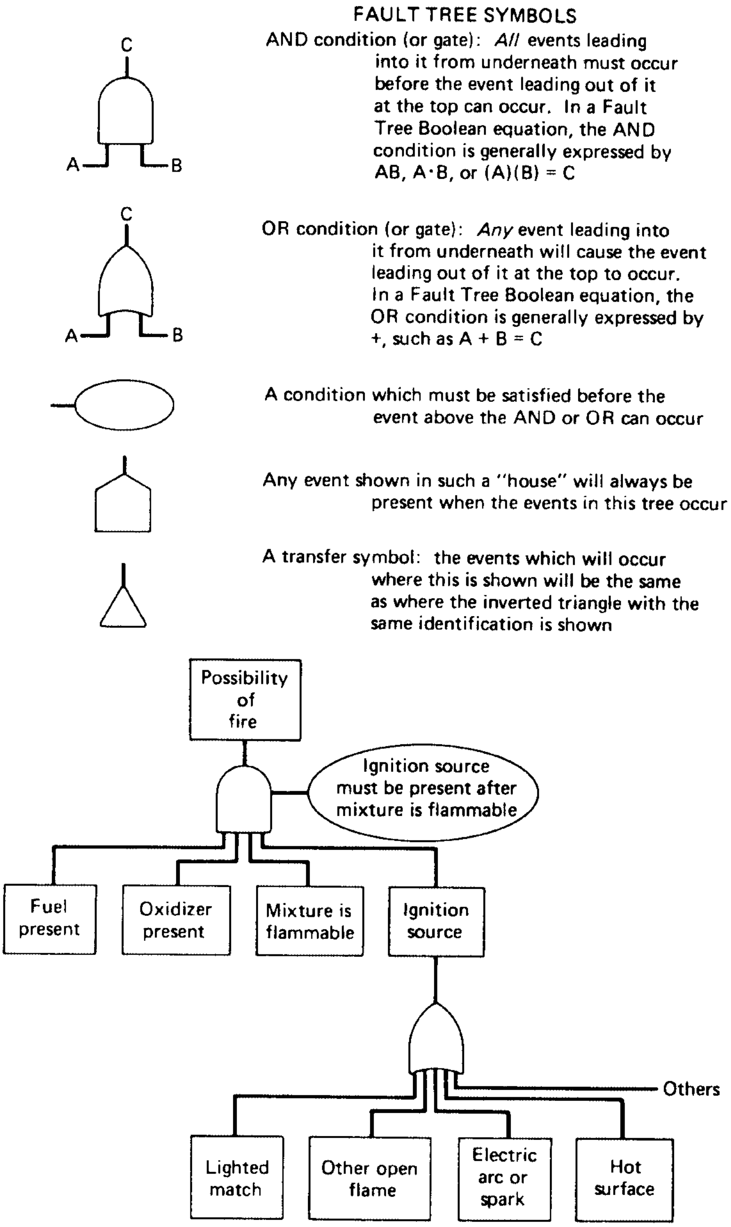

FAULT TREE SYMBOLS

AND condition (or gate): *All* events leading into it from underneath must occur before the event leading out of it at the top can occur. In a Fault Tree Boolean equation, the AND condition is generally expressed by AB, A·B, or (A)(B) = C

OR condition (or gate): *Any* event leading into it from underneath will cause the event leading out of it at the top to occur. In a Fault Tree Boolean equation, the OR condition is generally expressed by +, such as A + B = C

A condition which must be satisfied before the event above the AND or OR can occur

Any event shown in such a "house" will always be present when the events in this tree occur

A transfer symbol: the events which will occur where this is shown will be the same as where the inverted triangle with the same identification is shown

C
A
B
C
A
B
Possibility of fire
Ignition source must be present after mixture is flammable
Fuel present
Oxidizer present
Mixture is flammable
Ignition source
Others
Lighted match
Other open flame
Electric arc or spark
Hot surface

FIGURE 10.4 Fault tree analysis symbols. Fault tree analysis of fire. (Reprinted with permission from Hammer, W., *Occupational Safety Management and Engineering, 4th ed.,* Prentice-Hall, Englewood Cliffs, New Jersey, 1989, p. 558.)

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3. To optimize the allocation of resources to the safety program and to organizational hazard-control efforts

MORT programs and their associated training courses place emphasis on constructing trees for individual program needs and on a set of ready-made MORT trees that can be used for program design, program evaluation, or accident investigation.

EG&G Idaho, Inc. (P.O. Box 1625, Idaho Falls, ID 83415) is one of the primary users and developers of MORT and offers training courses in MORT application.

SUMMARY

Safety is important for all industries. The high costs associated with accidents, including injuries, facility damage, equipment downtime, and product loss, make it critical for the manager to understand and control the conditions that can lead to accidents.

The best way to minimize hazards is to thoroughly study the production requirements for a facility and determine which operations are absolutely necessary. Follow the materials from the beginning of the process to final shipment from the facility. Unnecessary processes and handling of material should be eliminated, and the remaining essential tasks should be analyzed to determine the safest and most efficient methods possible. Mechanical, rather than manual, means of handling materials should be used whenever possible. Employees should be aware of the hazards associated with their jobs and know how to minimize those hazards.

To be effective, management must take responsibility for initiating and enforcing a strong safety plan. The most effective safety programs will have both management commitment and employee involvement. Frontline supervisory staff must be convinced of the importance of safety and be held accountable for enforcing employee compliance with safe work practices. Regular inspections of the work environment, equipment, and work practices as well as initial training and periodic retraining of employees will help ensure that the work environment remains as safe as possible. Mechanical safety features, safe operating procedures, and emergency response procedures should be considered during the design phase, and methods for continued verification procedures to ensure that these safety elements remain effective should be built into the design.

Industrial engineers are in a unique position to influence worker safety since they design and redesign work environments. Thoughtful consideration of safety in the design phase can help maximize productivity by minimizing downtime and lost time associated with accidents. Failure to consider safety in the design phase can result in costly (in both human and dollar terms) accidents and injuries and may require subsequent redesign to correct safety hazards introduced by new processes or procedures.

Some basic principles of occupational safety have been presented in this chapter. For further information relating to OSHA regulations, refer to the OSHA General Industry Standards (29 CFR 1910) and Construction Standards (29 CFR 1926). Readers are also directed to the numerous standards and recommended practices developed by other organizations (often referenced in the OSHA standards) that apply to their particular applications. A vast array of information is available on the Internet. For more information, refer to Safety & Health on the Internet [58]. The following organizations may be helpful in determining which safety programs and materials are necessary for particular facilities and operations:

American Society of Safety Engineers (ASSE)
1800 E. Oakton Street
Des Plaines, IL 60018
(847) 699-2929
http://www.asse.org

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National Institute for Occupational Safety and Health (NIOSH)
U.S. Department of Health and Human Services
4676 Columbia Parkway
Cincinnati, OH 45226-1998
(800) 356-4674
http://www.cdc.gov/niosh

National Safety Council (NSC)
1121 Spring Lake Drive
Itasca, IL 60143-3201
(630) 285-1121
http://www.nsc.org

Occupational Safety and Health Administration (OSHA)
U.S. Department of Labor
Department of Labor Building
200 Constitution Avenue, NW
Washington, DC 20210
(202) 219-8148
http://www.osha-slc.gov

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BIOGRAPHIES

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CHAPTER 6.11

ERGONOMIC EVALUATION TOOLS FOR ANALYZING WORK

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Industry has become increasingly concerned with the negative effects that poor ergonomic conditions can have on their workforce and on productivity. Larger companies, especially those with an active corporate staff, have engaged the services of professional ergonomists to help perform ergonomic evaluation and set up an ergonomics program within a facility. Some companies have not addressed this problem adequately because of the apparent expense and the need for a professional specialist who could not be occupied full-time. Consultants have helped to fill this role; however, many companies still have no formal method for ergonomic evaluations and an ergonomics program structure.

Industrial engineers and system designers have the responsibility for designing workplaces, methods, and tooling for a wide variety of tasks in industry. The ergonomic stress to be imposed on an employee working at one of these tasks is determined when the job is designed. The optimum correction for ergonomic stress is to design these stresses out of the job. Engineers must therefore be equipped with adequate training and the proper techniques for evaluation of ergonomic stress. This chapter first addresses why there is a need for a comprehensive ergonomics program and how these elements apply to different size companies. Second, it examines how the ergonomic evaluation expands on that element of the ergonomics program that focuses on providing choices of metrologies and approaches for performing an ergonomic evaluation to the industrial engineer. This chapter is not to be used as a blueprint for an ergonomic evaluation process, but as an explanation of how various ergonomic tools can be applied. This article will inform the industrial engineer why an evaluation is necessary, the steps required to perform and document an evaluation, and the follow-up required to successfully use the results. Throughout the discussion, proper procedures and tools available such as a data collection matrix, training, guidelines, and software will be presented to complete a thorough, yet timely evaluation.

INTRODUCTION

Ergonomics is an applied science where the characteristics of people are used in designing jobs, tools, equipment, buildings, and environments with safety, quality, and high productivity as the goals. Industrial engineers design manufacturing and service systems to be used by people. Therefore, human interface design of the system is the responsibility of the industrial engineer, who needs to involve and acquire help from other human structure and function experts (e.g., Certified Professional Ergonomists and professionals in psychology, sociology, social psychology, human kinetics, and kinesiology). Since industrial engineers deal with the whole system (equipment and human resources), they are best equipped to analyze the effect of different solutions to an ergonomic problem and its impact on such a system. For each ergonomic question there is more than one answer. Some answers may fix the local problem but have an overall negative effect on the system, thereby suboptimizing the system. Therefore, it is very important to properly evaluate how ergonomic improvements impact the overall operation. As with any problem solving, a process should be defined and followed so that information can be gathered and analyzed to make a proper decision. In the case of ergonomic evaluation, a good process should also be defined and followed, and there are a variety of tools that can be used to evaluate ergonomic stress. In this chapter, many available tools will be discussed and their use within the evaluation process will be defined.

OVERALL ERGONOMIC PROGRAM

A well-defined and documented ergonomics program should be in place for any company. This program can vary in size and scope depending on the size of the company. However, each part of the program should be considered as to how it would be handled within the context of the company.

There are seven main steps to a comprehensive ergonomics program:

1. Employee and workplace audit
2. Ergonomic evaluation
3. Ergonomic redesign of workplaces, methods
4. Ergonomic program organization
5. Education and training program
6. Fitness and rehabilitation program
7. Reporting, feedback, and follow-up

The second step, ergonomic evaluation, will be discussed in detail in a subsequent section. For a very small company with one industrial engineer, the first three steps are essential to determine which of the jobs are potential ergonomic problems. The remaining four steps should be considered in a small company atmosphere, but their roles will be limited.

The first three steps are accomplished by reviewing injury history of the jobs, absentee reports, and other plant data. Understanding the type of injury and the reasons for absenteeism will determine the need for the next step. Next, the industrial engineer performs an ergonomic evaluation, and then redesigns the job.

The remaining four steps are then addressed. They involve tracking problems and remedies, communicating the progress of evaluations, educating all employees, and tracking future incidents as they arise. In a comprehensive program, each step should be addressed in some depth. A brief description of each element or step is presented in the following sections.

Employee and Workplace Audit

The audit will document work practices of the employees through the aid of employee feedback and by the physical observation of the design and method. The relationship between employee feedback and workplace design observation, versus injury history, will be determined from this audit. From the audit, a list of operations that should receive immediate attention regarding improvements will be made.

Ergonomic Stress Evaluation

The ergonomic stress evaluation of the operations on the list will be made using a variety of tools. Ergonomic problems can then be identified and pinpointed during this step. This topic will be discussed in great detail later in this chapter.

Ergonomic Redesign of Workplaces and Jobs

Based on the results of the audit and ergonomic stress evaluation, the products, workplace, and jobs may have to be redesigned or controlled to meet human aspects and requirements. This activity will integrate the ergonomic component with an engineered process for productivity improvement. A combined effort to improve both the job ergonomics and economics could result in synergistic effects and attractive cost reductions.

To the greatest possible extent, the objective of this phase is to adapt the physical and organizational work conditions to better fit the human physiology. Ideal operator positions (sitting and standing) can be defined and applied in the design and modification of workplace.

Ergonomics Program Organization

It is critical to obtain the commitment and support of top management to implement an ergonomics program. Such a program will affect all employees in an organization, so it is essential to establish a project organization to support this. A steering committee will set the direction, review the project, and make necessary decisions. An ergonomics coordinator will be responsible for the projects and activities relating to ergonomic evaluations and improvements. This person will report to the steering committee. Involvement by the safety, union, engineering, maintenance, and medical departments is required.

Education and Training Program

To increase the awareness and understanding of ergonomics in the workplace, training on all levels of the organization will be structured and carried out. The relationship between job design and employee health will be reviewed as well as methods to reduce the risk of injury. The employees will be encouraged to discuss problems and improvement ideas pertaining to their own workplaces and jobs with management and/or the ergonomics coordinator. It is important to make training sessions and training material simple and understandable for all employees.

Fitness and Rehabilitation Program

By consulting with a human kinetics or a kinesiology professional in a medical department, a fitness program will be developed to improve individuals' physical capability as well as their psychological awareness and motivation to participate in the program.

The human kinetics or a kinesiology professional will also prescribe rehabilitation procedures for those individuals who have experienced a cumulative trauma disorder (CTD) or any other injury.

Reporting, Feedback, and Follow-up

The ergonomics program is a continuous improvement program linked to other industrial engineering programs such as productivity improvements and is based on methods engineering.

To assess the progress and results of ergonomic efforts and to meet OSHA requirements, a reporting and feedback system is developed to include employee feedback and injury monitoring. To ensure a safe work environment, a comprehensive approach to ergonomics must be established within a facility. This approach will ensure that

- Proper avenues for employee involvement and feedback are developed.
- Problems are properly identified, evaluated, and remedied.
- All of the effected parties (human resources, employees, engineering, union) can be involved in the process.

By following this program organization, all aspects of the ergonomic process will be considered. Problems and concerns will be properly identified, evaluated, and remedied, thus providing the company with valuable means to protect the workforce.

ERGONOMIC EVALUATION

Previously in an employee and workplace audit, a list of potential jobs associated with an ergonomic problem would have been identified through injury history, workers' complaints, and absenteeism records. *An ergonomic problem exists when there is a poor match between a person's physical capability and job demands.* This is why we need to perform an ergonomic evaluation. Ergonomic problems can be very simple to identify, and other times very difficult. Even for what may appear simple, there may be many remedies.

For example, if *a package the operator is lifting is too heavy,* preliminary observation will provide some obvious remedies. One may be to reduce the package size to within operator capability; this may reduce the severity of each single lift. However, the impact on the rest of the system may be an increase in quantity of packages, packing material, and more labor to handle more packages, therefore raising the overall product cost in terms of labor and material. Another remedy may be to use a material-handling device (lift assist) to reduce the weight of the package to the operator. This remedy does not increase the number of packages and packing material in the rest of the system, but still may use more labor since these devices generally slow the operator down as compared with the manual method.

To thoroughly investigate possible remedies to an ergonomic problem, a structured approach should be taken to ensure that the proper consideration is given to the problem. Based on the diverse and complex nature of the problem, some aspects will be more thorough than those for less complex problems.

There are six basic steps to performing a thorough ergonomic evaluation:

1. Preliminary information gathering
2. Instruments for data collection
3. On-the-job observation, operator self-evaluation, data collection, and posture analysis
4. Ergonomic analysis
5. Recommendations
6. Documentation

All of these steps are essential to performing a thorough ergonomic evaluation. The difference between a simple and a more complex problem is the quantity of work for the analyst at each step. The remaining sections present a detailed breakdown of each step.

Preliminary Information Gathering

This is a preparation step to a good analysis and is many times overlooked. Here we need to collect information about the job:

- First, develop a layout of the job from the top and side views as required. The layout should be to scale and include all operator interfaces, buttons, switches, levers, heights, and locations of all items that the operator needs to perform the task.
- Next, detail the job instruction demonstrating a proper method. This method should include all the tools the operator needs to perform the job, corresponding frequencies, and the time it takes to do each task. This method may be available from the predetermined time system (such as MOST® or MTM) used to develop the labor standard.
- Understand the history of the job. Are there medical reports with cases of injuries relating to this job? What are the details of injuries? Is this a new employee just getting used to the job?
- Gather information on operator-specific issues. What is the current history of the operator to be observed? Does the operator have an injury or restrictions?

Instruments for Data Collection

From preliminary information gathering, determine what tools to use to collect good data. Some of the tools are

- Force gauge—to measure the push, pull, lift, and carry forces
- Temperature gauge—to record ambient temperature (environmental condition)
- Grip strength gauge—an indirect way of measuring grip force
- Light meter—to measure available light to do the task (environmental condition)
- Measuring tape—probably the most important instrument to verify all workstation dimensions (e.g., heights, reach, the height of the employee).
- Stop watch—to verify the cycle time of the tasks
- Video or still camera—to assist method and posture analysis by others away from the actual job

On-the-Job Observation, Self-Evaluation, Data Collection, and Posture Analysis

On-the-Job Observation. This is probably the most important step. Make sure that you are observing the prescribed method and make notes on postures used by the operator by filling out the data collection matrix described later in Fig. 6.11.2. When recording postures, it is very important to know the operator overall height (stature), anthropometric data, elbow height, and shoulder height. This will help determine this operator's percentile in our population (Is the operator a 5th percentile female or a 50th percentile male?). Depending on the severity and resources available, it is a good idea to take still pictures or to videotape the job so that it can be used in laboratory analysis later. Here you could have others observe the job without disrupting it. Some care should be taken in making a video to ensure the camera is level and pointed perpendicular to the operator. It would also be helpful to have some dimension markers on objects. This is a simple approach of attaching Post-it® notes to mark height dimensions in a still picture or video. This is like putting a ruler in a still picture to get the relative size of the object in the picture.

Operator Self-Evaluation. Every analyst should talk to multiple operators and get their input. You may discover that the problem is other than ergonomic such as a problem with the supervisor or a home recreational physical activity. The operator will tell you where it hurts, when it hurts, and how much effort they perceive it takes to do each step of the job. One possible tool here could be the overall rating of the perceived exertion or the overall rating of physiological effort: Borg Scale [1].

Data Collection. The Job Design Data Collection Matrix, as shown in Fig. 6.11.1, is used to aid in an ergonomic analysis. This data collection matrix allows a user to collect information for the ergonomic evaluation tools used in this study, which are explained later. *You are free to use this blank form for your data collection.*

The evaluation tools that will use this data collection matrix are

- RULA (rapid upper limb assessment) [2]
- NIOSH's two-handed dynamic lifting [3]
- University of Michigan's 2D, 3D static analysis [4]
- Snook and Ciriello's push/pull/carry tables [5]
- ErgoMOST [6]
- University of Michigan's Energy Expenditure Prediction Program [7]

These tools will be discussed in further detail in later sections.

The matrix allows the user to collect posture, dimension, and time data. This data is then tabulated for each step of the method. The first data to be discussed is the postural data collection.

Posture Analysis. Posture analysis is a very important part of an ergonomic evaluation because there is a great variation in what type of force the body can handle due to the posture that the body is in. This posture analysis is essential for doing any type of biomechanical analysis. The posture analysis codes to be used in the matrix are the same as ErgoMOST inputs. ErgoMOST is an ergonomic evaluation tool that analyzes methods to determine ergonomic risk and will be discussed later in this section.

Posture analysis is probably the most difficult step in the data collection process, and having a video or still pictures for further analysis would make this step easier. For example, wrist postures can be difficult to observe because of only small angles of deviations and short duration of occurrence (another reason for video analysis). Wrist postures have five types of deviations:

1. Wrist flexion—bending the wrist down
2. Wrist extension—bending the wrist up
3. Ulnar deviation—bending the wrist towards the little finger
4. Radial deviation—bending the wrist toward the thumb
5. Wrist twist—rotation of the wrist and the lower arm also called:

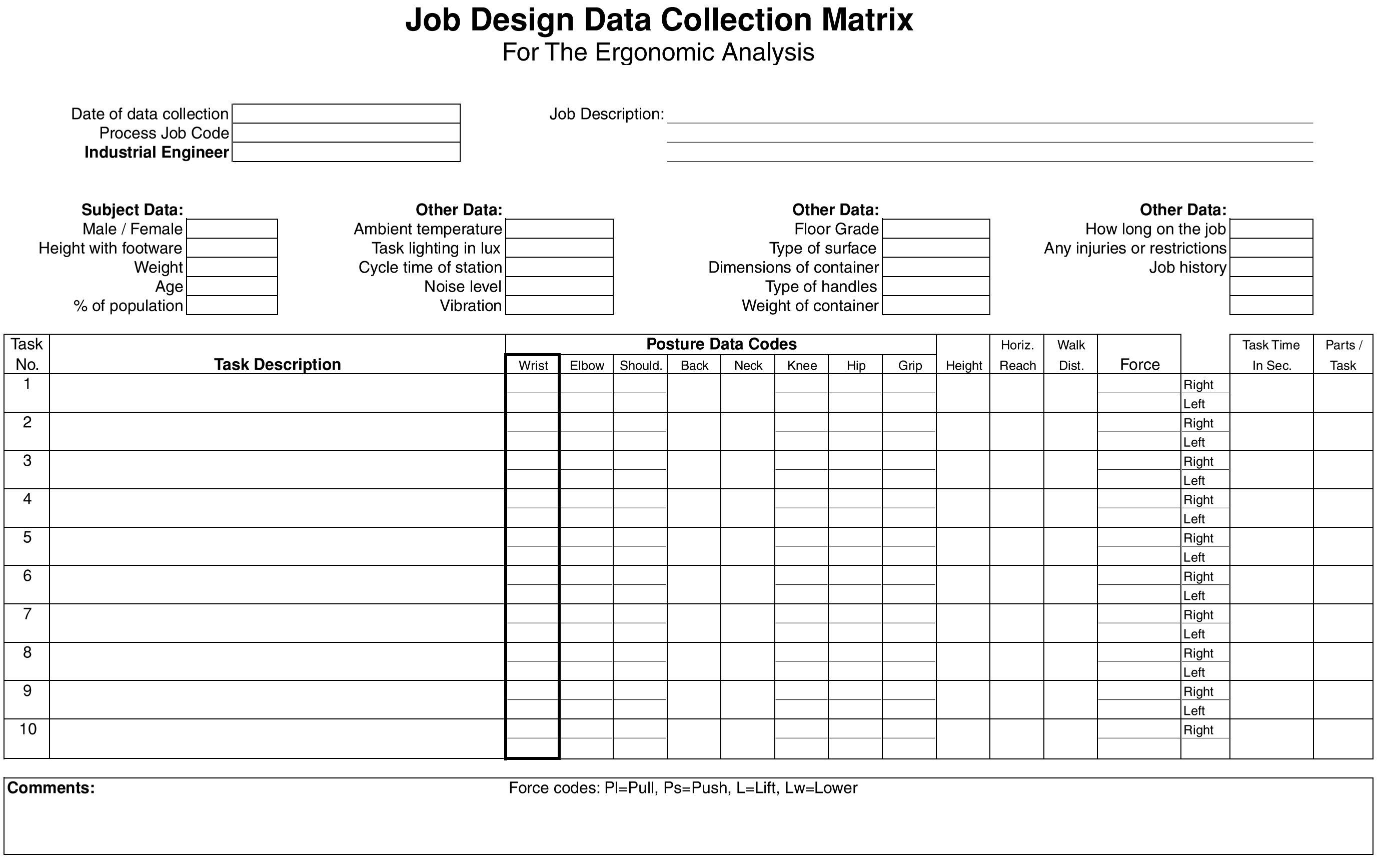
   Pronation—rotating of the thumb towards the body

   Supination—rotating of the thumb away from the body

You have to be able to recognize these types of deviations and categorize their magnitude from the neutral position (shown in later illustrations).

If you look at your own wrist and demonstrate the radial deviation by bending your wrist toward the thumb as far as possible, you can see that the wrist bending range is approximately only 25° from neutral. From this demonstration it is clear that the best the observer can do is determine whether the wrist posture is neutral, low radial, or high radial deviation.

Following are the wrist and elbow posture pictures and codes to be used in the proposed data collection matrix. A sample of the filled-out table is in the section, Ergonomic Analysis. All task descriptions are broken out separately for GET and PLACE moves. For example, GET and PLACE identify the worst postures used for left and right joints. In our example, if the left and right elbows are in a high extension posture then the code noted in the data collection matrix is EH (see Fig. 6.11.2).



Job Design Data Collection Matrix

For The Ergonomic Analysis

Date of data collection
Process Job Code
Industrial Engineer

Job Description:

Subject Data:
Male / Female
Height with footware
Weight
Age
% of population

Other Data:
Ambient temperature
Task lighting in lux
Cycle time of station
Noise level
Vibration

Other Data:
Floor Grade
Type of surface
Dimensions of container
Type of handles
Weight of container

Other Data:
How long on the job
Any injuries or restrictions
Job history

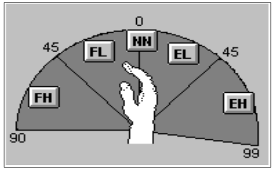
Task		**Posture Data Codes**									Horiz.	Walk			Task Time	Parts /
No.	**Task Description**	Wrist	Elbow	Should.	Back	Neck	Knee	Hip	Grip	Height	Reach	Dist.	Force		In Sec.	Task
1														Right Left		
2														Right Left		
3														Right Left		
4														Right Left		
5														Right Left		
6														Right Left		
7														Right Left		
8														Right Left		
9														Right Left		
10														Right		

Comments:

Force codes: Pl=Pull, Ps=Push, L=Lift, Lw=Lower

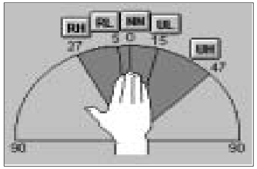
FIGURE 6.11.1 Blank data collection matrix.

Wrist and Elbow Posture Codes



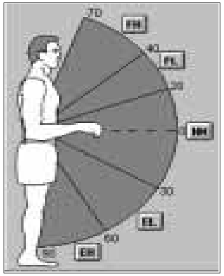
Wrist Flexion / **Extension** Posture Codes for the Data Collection Matrix

Code	Angle from Neutral	Description
FH	45 to 90	Flexion High
EH	45 to 99	Extension High
FL	0 to 45	Flexion Low
EL	0 to 45	Extension Low
NN	0	Neutral



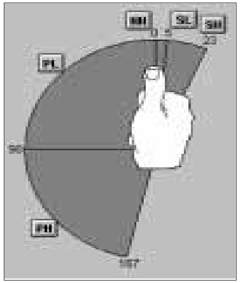
Wrist Deviation Posture Codes for the Data Collection Matrix

Code	Angle from Neutral	Description
UH	15 to 47	Ulnar Deviation High
RH	5 to 27	Radial Deviation High
UL	0 to 15	Ulnar Deviation Low
RL	0 to 5	Radial Deviation Low
NN	0	Neutral



Elbow Flexion / **Extension** Posture Codes for the Data Collection Matrix

Code	Angle from Neutral	Description
EH	60 to 90	Extension High
FH	40 to 70	Flexion High
EL	30 to 60	Extension Low
FL	20 to 40	Flexion Low
NN	0 to 20 Flexion 0 to 30 Extension	Neutral



Elbow Posture Codes (Wrist or Forearm Twist) for the Data Collection Matrix

Code	Angle from Neutral	Description
PH	90 to 167	Pronation High
SH	5 to 23	Supination High
PL	0 to 90	Pronation Low
SL	0 to 5	Supination Low
NN	0	Neutral

FIGURE 6.11.2 Wrist and elbow posture codes.

Ergonomic Analysis

After you have filled in the Job Design Data Collection Matrix, you need to do an ergonomic analysis. Figure 6.11.3 depicts an example problem for our analysis. The box size being handled in this example is

- 41 cm (16 in) × 41 cm (16 in) × 30.5 cm (12 in) and the weight is 11.3 kg (25 lb)
- Time to load or unload the box to and from the cart is 10 sec
- Time to push the full cart is 30 sec, and to pull the empty cart is 20 sec

Figure 6.11.4 shows the data collection matrix filled out for this example.

Industrial Engineering Ergonomics Toolbox: Major Tools. The following is a list of some major and most widely used tools industrial engineers should consider for their ergonomics toolbox.

- *Posture data collection*—a must for every analysis
  - Anthropometric data analysis
  - Upper limb checklist (e.g., RULA)
  - Load limits for lifting (e.g., the NIOSH equation)
  - Lumbar spine forces and strength demands analysis (e.g., University of Michigan's 2D, 3D analysis and University of Waterloo's WATBAK [8])
  - Push/pull/carry analysis (e.g., Snook and Ciriello, and Mital [9])
  - Force, posture, repetition, grip, and vibration ergonomic analysis (e.g., ErgoMOST)
  - Metabolic energy cost analysis (e.g., University of Michigan's Energy-Expenditure)
- Ergonomic line balance
- Other tools
  - Recovery time for repetitive work [10], [11]
  - Borg RC-10
  - Ovako Working Posture Analyzing System (OWAS) [12]

Table 6.11.1 can help in determining which tools to use depending on the type of task. Following is a brief discussion of one tool from each category of major tools. The results for our example are summarized in a table in the Recommendation section.

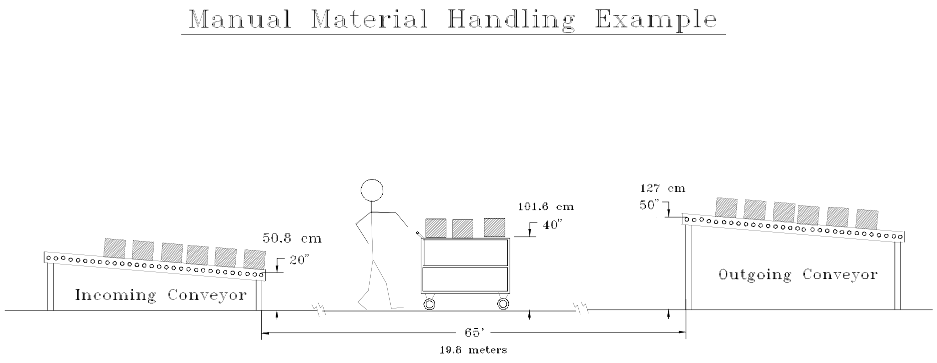


FIGURE 6.11.3 Manual material handling example.

Job Design Data Collection Matrix

For The Ergonomic Analysis

Date of data collection: October 29, 1997
Process Job Code: Supermarket Stock
Industrial Engineer: Dan Cerovec

Job Description: Move boxes from incoming conveyor to the outgoing conveyor

Subject Data:

Male / Female	M
Height with footware	6 Feet
Weight	225 lbs
Age	42 yrs
% of population	90 %ile

Other Data:

Ambient temperature	75 F
Task lighting in lux	
Cycle time of station	36.7 sec
Noise level	
Vibration	

Other Data:

Floor Grade	
Type of surface	
Dimensions of container	18"x16"x12"
Type of handles	None
Weight of container	25 lbs

Other Data:

How long on the job	1 year
Any injuries or restrictions	No
Job history	None

Task No.	Task Description	Posture Data Codes														
		Wrist	Elbow	Should.	Back	Neck	Knee	Hip	Grip	Height	Horiz. Reach	Walk Dist.	Force		Task Time In Sec.	Parts / Task
1			EH				F3	F2	W				12.5L	Right		
	Get boxes from incoming conveyor		EH		F3		F3	F2	W	20"	16"	3'	12.5L	Left	5	1
2		UH		F3BL2					W				12.5L	Right		
	Place boxes to cart	UH		F3BL2					W	40"	16"		12.5L	Left	5	1
3			EH	F3					W				10PS	Right		
	Push cart to outgoing conveyor		EH	F3					W	44"	12"	65'	10PS	Left	30	3
4		UH	EL	F3BL2					W				12.5L	Right		
	Get boxes from cart	UH	EL	F3BL2					W	40"	16"		12.5L	Left	5	1
5		UH		ABM					W				12.5L	Right		
	Place boxes to outgoing conveyor	UH		ABM					W	50"	16"	3'	12.5	Left	5	1
6		NN	EH	F3					W	44"	16"	65'	5PL	Right	20	3
	Pull cart back to start													Left		
7														Right		
														Left		
8														Right		
														Left		
9														Right		
														Left		
10														Right		
														Left		

Comments: Force codes: Pl=Pull, Ps=Push, L=Lift, Lw=Lower

FIGURE 6.11.4 Completed matrix.

ERGONOMIC EVALUATION TOOLS FOR ANALYZING WORK

TABLE 6.11.1 Tool Usage Matrix

		Static		Dynamic			
Type of task	RULA	U. of M. 2D	U. of M. 3D	Snook Ciriello	NIOSH 1991	Ergo MOST	U. of M. energy expenditure
Sagittal 1 hand lift		X	X			X	
Asymmetric (twisting) 1 hand lift			X			X	
Sagittal 2 hand lift	X	X	X	X	X	X	
Asymmetric (twisting) 2 hand lift			X		X	X	
Push/pull		X	X	X		X	
Carrying loads		X	X	X		X	X

Anthropometric Data Analysis. Anthropometric data, for our use, is the measurement of human body external characteristics such as the functional forward reach, stature (overall height), and elbow height. This is probably the most powerful tool in the industrial engineer's ergonomics toolbox. Anthropometric data forms the foundation in the design of the ergonomically sound workstation. For example, in the standing side view position, the following dimensions from Table 6.11.2 may be of interest. (This data was adopted from Table 4.29 in Stephen Pheasant's "Bodyspace" [13].)

TABLE 6.11.2 Anthropometric Data

	Male 95th Percentile		Female 5th Percentile	
	cm	in	cm	in
Stature	187.0	73.6	152.0	59.8
Shoulder height	155.0	61.0	122.5	48.2
Elbow height	119.0	46.8	94.5	37.2
Knuckle height	83.0	32.7	67.0	26.4
Shoulder—grip length	72.5	28.5	56.0	22.1
Vertical grip reach	221.0	87.0	180.5	71.5

Each industrial engineer needs to establish anthropometric data for the population in their environment. This data may be different from one manufacturing facility to another or from one country to another. If data is not available from the human resources department, then do some sampling and make adjustments to data from other populations. Design parameters need to be established as to what percentage of the population we want to protect. Designing for the average 50th percentile person is a myth since these people don't exist. Designing for 100 percent of the population would mean going to the *Guinness Book of Records* for anthropometric data. The most common approach is to design for the 5th to 95th percentile of the population, which means that the job will not fit 10 percent of the population. Following are some critical design parameters:

- The forward-reach distance should be designed for the capability of the 5th percentile person.
- Clearance dimensions should be based on the 95th percentile person.

- Manual work is best performed just below the elbow height.
- Physical load carrying is best around waist height.

The most important rule in workspace height design is to err on the high side, since it is easier to add a platform than dig a hole. Do not forget the matting and shoe allowance factors in the anthropometric data. A discussion with the ergonomics team to determine the right working height for a new workstation should take place. This discussion is worthwhile since modifying the workstation after installation is difficult. The data collected from the job in your data collection matrix should fit your design parameters.

Figure 6.11.5 is a side view (sagittal plane) of a 5th percentile female and a 95th percentile male functional horizontal reach. It is helpful to draw this graph for your population, and it should be used in designing and evaluating the forward reach envelope of tasks. The cross-hatched area represents a functional reach without bending for 90 percent of the previously described population. In our example, the incoming conveyor is below the functional reach of the 5th percentile female and 95th percentile male without bending. The outgoing conveyor is above the shoulder height of the 5th percentile female. Both of these conditions are not desirable. Now it is necessary to assess the degree of deviation of postures from our parameters using a posture analysis tool.

RULA. The rapid upper limb assessment is a survey method for the investigation of work-related upper limb ergonomic problems. It is a simple method to use since all it requires is a trained eye, analysis forms, and a pencil. This assessment divides the posture analysis into two groups:

1. Arm and wrist analysis—sagittal plane or side view
    a. Score the upper arm posture.
    b. Score the lower arm posture.
    c. Score the wrist posture.
    d. Combine the arm and wrist scores from a table based on the individual scores [2].
    e. Add a muscle score, which is based on the type of posture. Is it static or does it repeat the same action more than four times a minute (repetitive)?
    f. Add a force load score.
    g. *Subtotal the arm and wrist score.*
2. Neck, trunk, and leg analysis—sagittal plane or side view
    a. Score the next posture.
    b. Score the trunk posture.
    c. Score the leg posture.
    d. Combine the neck, trunk, and leg scores from a table based on the individual scores [2].
    e. Add a muscle score, which is based on the type of posture. Is it static or does it repeat the same action more than four times a minute (repetitive)?
    f. Add a force load score.
    g. *Subtotal the neck, trunk, and leg score.*
    h. *Total the final score, which is the overall rank for that task* [2].

The overall score can range from 1 to 7. A job with a score of 1 is acceptable and a score of 7 requires an immediate redesign. More information on how RULA works and what the forms look like can be found in Ref. 2. The results of the example analysis using this tool are in the Recommendations section. The next tool will be used to analyze the lifting portion of our example task.

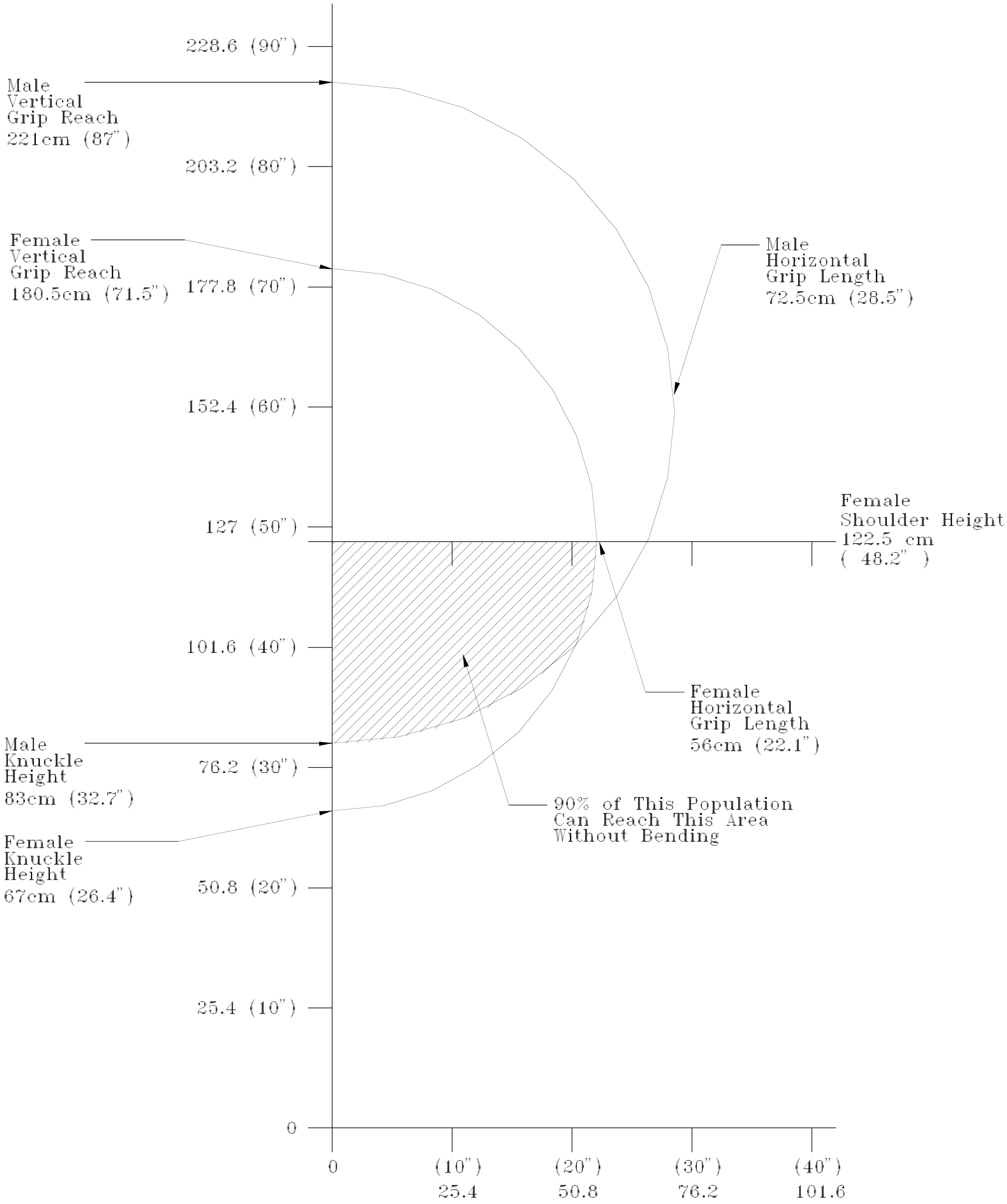


FIGURE 6.11.5 Functional reach for the 5th percentile female to 95th percentile male population.

Revised 1991 NIOSH Lifting Equation (Dynamic Lifts). The lifting equation was designed to estimate physical stress of two-handed manual lifting tasks. A *lifting task* is defined as grasping an object with two hands and lifting it vertically through space without any assistance. The NIOSH equation calculates the recommended weight limit (RWL). If the RWL is equal to or greater than the actual weight of the part being lifted, then the task is an acceptable ergonomic risk. Since load constant (LC) = constant 23.1 kg (51 lb), all we have to calculate are six variables (see Table 6.11.3), or in this equation, six multipliers (M). Each multiplier has no effect or a negative effect on the LC. This means that the maximum weight a person can lift is 23.1 kg (51 lb) under optimal condition. The NIOSH equation:

TABLE 6.11.3 NIOSH Formulas

			Metric	U.S. customary
LC	=	Load constant	23 kg	51 lb
HM	=	Horizontal multiplier	(25/H)	(10/H)
VM	=	Vertical multiplier	1 – (.003/V-75/)	1 – (.0075/V-30/)
DM	=	Distance multiplier	.82 + (4.5/D)	.82 + (1.8/D)
AM	=	Asymmetric multiplier	1 – (.0032A)	1 – (.0032A)
FM	=	Frequency multiplier	Table F [3]	Table F [3]
CM	=	Coupling multiplier	Table C [3]	Table C [3]

$$\text{RWL} = \text{LC} \times \text{HM} \times \text{VM} \times \text{DM} \times \text{AM} \times \text{FM} \times \text{CM}$$

where H = the horizontal distance from the midpoint between the ankles (the most common mistake is measuring the distance from the front on the stomach) to the midpoint of where the hands grasp the object being lifted. The distance can't be less than 25.4 cm (10 in) or more than 63.5 cm (25 in), which on some anthropometry tables is the maximum horizontal reach of the 5th female percentile (see Table 6.11.4). After 63.5 cm (25 in), the multiplier is defined to be 0, which makes RWL = 0.

V = the vertical distance from the floor to the point where the hands grasp the object. Origin and the destination height must be between 0 and 177.8 cm (70 in) where 177.8 cm on some anthropometric tables is the maximum overhead reach for 5th percentile female population.

D = the vertical distance of lift and has a range of 25.4 cm (10 in) – 177.8 cm (70 in).

A = the estimated angle (angle asymmetry) of how much the body is twisted relative to the sagittal plane (see Table 6.11.5).

F = the frequency of lifts per minute. To get the multiplier you match up the frequency with one of the duration categories (8 hours, 2 hours, 1 hour) and a V category (V < 76.2 cm [30 in], V > 76.2 cm [30 in]) from the table. Fifteen lifts per minute in any category equals a multiplier of 0, and RWL = 0.

C = the coupling multiplier that describes the interface between the hands and the object lifted. There are three categories of C: G (good—optimal size object with handles), F (fair—optimal size object with no handles, or not optimal size but with handles), and P (poor—object not optimal size and no handles). To calculate the multiplier, consult a table and match up C with a V category, as you did for F (see Table 6.11.6).

Figures 6.11.6 and 6.11.7 show our example calculated using U.S. customary and metric units.

University of Michigan's 2D and 3D Static Strength Prediction Model Programs. The model programs will analyze the back compressive forces required to perform the task (lifts, presses, pushes, and pulls). Neither program is appropriate for analyzing risk in highly dynamic or repetitive tasks. They are used for low frequency high force demand tasks.

ERGONOMIC EVALUATION TOOLS FOR ANALYZING WORK

TABLE 6.11.4 Horizontal Multiplier

H in	HM	H cm	HM
≤10	1.00	≤25	1.00
11	.91	28	.89
12	.83	30	.83
13	.77	32	.78
14	.71	34	.74
15	.67	34	.69
16	.63	38	.66
17	.59	40	.63
18	.56	42	.60
19	.53	44	.57
20	.50	46	.54
21	.48	48	.52
22	.46	50	.50
23	.44	52	.48
24	.42	54	.46
25	.40	56	.45
>25	.00	58	.43
		60	.42
		63	.40
		>63	.00

TABLE 6.11.5 Asymmetric Multiplier

Angle degree	AM
0	1.00
15	.95
30	.90
45	.86
60	.81
75	.76
90	.71
105	.66
120	.62
135	.57
>135	.00

TABLE 6.11.6 Coupling Multiplier

	CM	
Coupling type	V < 30 in	V ≥ 30 in
Good	1.00	1.00
Fair	.95	1.00
Poor	.90	.90

2D INPUT:

- Worker body posture (arms, back, and legs), or preset postures in the sagittal plane assumes symmetrical motions.
- Force magnitude, direction, and one- or two-handed task.
- Worker anthropometry or preset values.

2D OUTPUT:

- Percent of the male and female population that have the strength in each of the joints (elbow, shoulder, L5/S1 back, hip, knee, ankle) required to perform the task.
- Percent of the male and female population that can tolerate the back compressive forces required performing the task.

The 2D program is relatively easy to use compared to the 3D program. The 3D program has many more posture inputs because the analysis and inputs are in three dimensions. 3D analysis is better since most lifts in the real world are not symmetrical. More information on these programs can be obtained from the University of Michigan Center for Ergonomics. The results from using this tool are discussed in the Recommendations section.

Push, Pull, and Carry Tables—Stover H. Snook and Vincent M. Ciriello. Pushing carts is a two-handed, manual-handling dynamic task using the whole body (arms, back, legs). Push/pull tables are available from Ref. 5. These tables provide data for

- Pushing/pulling at six different heights
- 10 to 90 percent of the male and female population
- Task frequencies from once per 6 seconds to once per 480 minutes
- Distance of push from 2.1 m (6.8 ft) to 61 m (200 ft)
- Initial forces—force required to put the cart in motion
- Sustained forces—force required to keep the cart in motion

NIOSH LIFT ANALYSIS WORKSHEET

DEPARTMENT Acme
JOB CODE Supermarket stock
INDUSTRIAL ENGINEER Dan Cerovec
DATE October 29, 1997

JOB DESCRIPTION:
Lift boxes from the incoming conveyor to a cart

STEP 1 Record task variables

Object Weight (lbs)		Hand Location (in)				Vertical Distance (in)	Asymmetric Angle (degrees)		Frequency Lifts / Min.	Duration (HRS)	Object Coupling
		Origin		Destination			Origin	Destination			
L (AVG)	**L (MAX)**	**H**	**V**	**H**	**V**	**D**	**A**	**A**	**F**		**C**
	25	16 "	20"	16"	40"	20"	0	0	1.63	8	Fair

STEP 2 Look up multipliers and calculate the RWLs

	RWL =	**LC**		**HM**		**VM**		**DM**		**AM**		**FM**		**CM**		
ORIGIN	**RWL =**	51 lbs	X	0.63	X	0.93	X	0.91	X	1.0	X	0.65	X	0.95	=	16.79 lbs
				Table H		**Table V**		**Table D**		**Table A**		**Table F**		**Table C**		
DESTINATION	**RWL =**	51 lbs	X	0.63	X	0.93	X	0.91	X	1.0	X	0.65	X	0.95	=	16.79 lbs

STEP 3 Calculate the lifting index

ORIGIN **LIFTING INDEX =** $\dfrac{\text{OBJECT WEIGHT (L)}}{\text{RWL}} = \dfrac{25 \text{ lbs}}{16.79 \text{ lbs}} = \boxed{1.49}$

DESTINATION **LIFTING INDEX =** $\dfrac{\text{OBJECT WEIGHT (L)}}{\text{RWL}} = \dfrac{25 \text{ lbs}}{16.79 \text{ lbs}} = \boxed{1.49}$

FIGURE 6.11.6 NIOSH lift analysis worksheet—U.S. customary units.

NIOSH LIFT ANALYSIS WORKSHEET

DEPARTMENT Acme
JOB CODE Supermarket stock
INDUSTRIAL ENGINEER Dan Cerovec
DATE October 29, 1997

JOB DESCRIPTION:
Lift boxes from the incoming conveyor to a cart

STEP 1 Record task variables

Object Weight(kg)		Hand Location (cm)				Vertical Distance (cm)	Asymmetric Angle (degrees)		Frequency Lifts / Min.	Duration (HRS)	Object Coupling
		Origin		Destination			Origin	Destination			
L (AVG)	**L (MAX)**	**H**	**V**	**H**	**V**	**D**	**A**	**A**	**F**		**C**
	11.34	40.64	50.8	40.64	101.6	50.8	0	0	1.63	8	Fair

STEP 2 Look up multipliers and calculate the RWLs

	RWL =	**LC**		**HM**		**VM**		**DM**		**AM**		**FM**		**CM**	
ORIGIN	**RWL =**	23 kg	X	0.60	X	0.93	X	0.90	X	1.00	X	0.65	X	0.95	= 7.13 kg
				Table H		**Table V**		**Table D**		**Table A**		**Table F**		**Table C**	
DESTINATION	**RWL =**	23 kg	X	0.60	X	0.93	X	0.90	X	1.00	X	0.65	X	0.96	= 7.13 kg

STEP 3 Calculate the lifting index

ORIGIN **LIFTING INDEX =** $\dfrac{\text{OBJECT WEIGHT (L)}}{\text{RWL}} = \dfrac{11.34\text{ kg}}{16.79\text{ kg}} = \boxed{1.59}$

DESTINATION **LIFTING INDEX =** $\dfrac{\text{OBJECT WEIGHT (L)}}{\text{RWL}} = \dfrac{11.34\text{ kg}}{16.79\text{ kg}} = \boxed{1.59}$

FIGURE 6.11.7 NIOSH lift analysis worksheet—metric units.

To analyze the job, you need a push/pull type force gauge with peak value freeze capability. You should have enough attachments to be able to push/pull many different objects. Take at least three different samples and use the average value. Compare this value to the value in one of the push/pull tables. If the value you sampled is greater than the one in the table, then there is a concern for endurance or the whole-body strength. Results from our example using this tool are in the Recommendations section.

ErgoMOST. ErgoMOST, a software tool developed by H. B. Maynard and Company, Inc., is designed to allow a user to analyze a defined method from an ergonomic standpoint. This analysis is then interpreted by ErgoMOST and presented to the user in easily understood terms. This tool is intended to provide some of the expertise of the ergonomist to the methods analyst so that ergonomic analysis can be performed as methods are developed. This feature allows for a greater coverage of jobs with ergonomic analysis.

ErgoMOST combines the analysis of a number of different ergonomic factors. They include force, posture, repetition, and grip and vibration stress. The goal of ErgoMOST is to allow the user to model an operator's work content for an entire shift. This is extremely helpful because the whole job is evaluated, not just one isolated piece of the job.

ErgoMOST requires that the method be defined. This method can be defined using the MOST technique through the use of MOST for Windows, or the MOST Data Manager. Those allow the user to build ergonomic analysis during the standards development phase. However, method steps can also be entered directly into ErgoMOST.

A group of method steps defining a job is analyzed in the Analysis module of the system creating an element known as an *Analysis.* ErgoMOST allows the user to combine these analyses together in the Process Module. The Process Module provides feedback for a job rotation or for operations performed on a product mix.

For each method step in an Analysis, the following information is required. This set of information can be captured in an element called an ErgoSet so that it may be reused as the same activity recurs in the method.

INPUT:

Method—A method description is required. They can be methods used to develop labor standards. The essential elements are the method description, the time, and the frequency of occurrence per cycle.

Force—The force required to perform the method.

Action—The action for each method description is defined as a Lift, a Push or a Pull.

Posture Input—Postures for each body member are defined per method description. The body members are

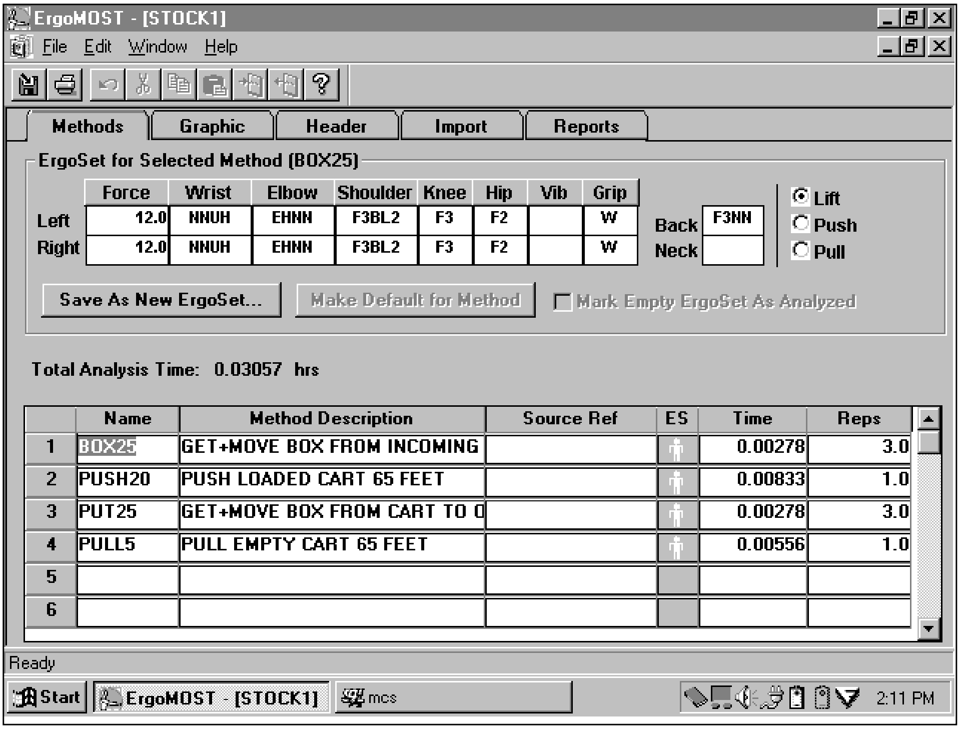
- Wrists
- Elbows
- Shoulders
- Back
- Neck
- Knees
- Hip

Vibration—Vibration rating for the right or left hand.

Population—The population of the operator is defined as male or female with the percentile (5th, 50th, or 95th).

Job Information—At the job level, the shift hours and the cycles per shift—product quantity—are needed to provide feedback for the operator's entire day of work.

ERGONOMIC EVALUATION TOOLS FOR ANALYZING WORK



ErgoSet for Selected Method (BOX25)

	Force	Wrist	Elbow	Shoulder	Knee	Hip	Vib	Grip
Left	12.0	NNUH	EHNN	F3BL2	F3	F2		W
Right	12.0	NNUH	EHNN	F3BL2	F3	F2		W

Back F3NN

Neck

● Lift
○ Push
○ Pull

☐ Mark Empty ErgoSet As Analyzed

Total Analysis Time: 0.03057 hrs

	Name	Method Description	Source Ref	ES	Time	Reps
1	BOX25	GET+MOVE BOX FROM INCOMING			0.00278	3.0
2	PUSH20	PUSH LOADED CART 65 FEET			0.00833	1.0
3	PUT25	GET+MOVE BOX FROM CART TO C			0.00278	3.0
4	PULL5	PULL EMPTY CART 65 FEET			0.00556	1.0
5						
6						

FIGURE 6.11.8 ErgoMOST input.

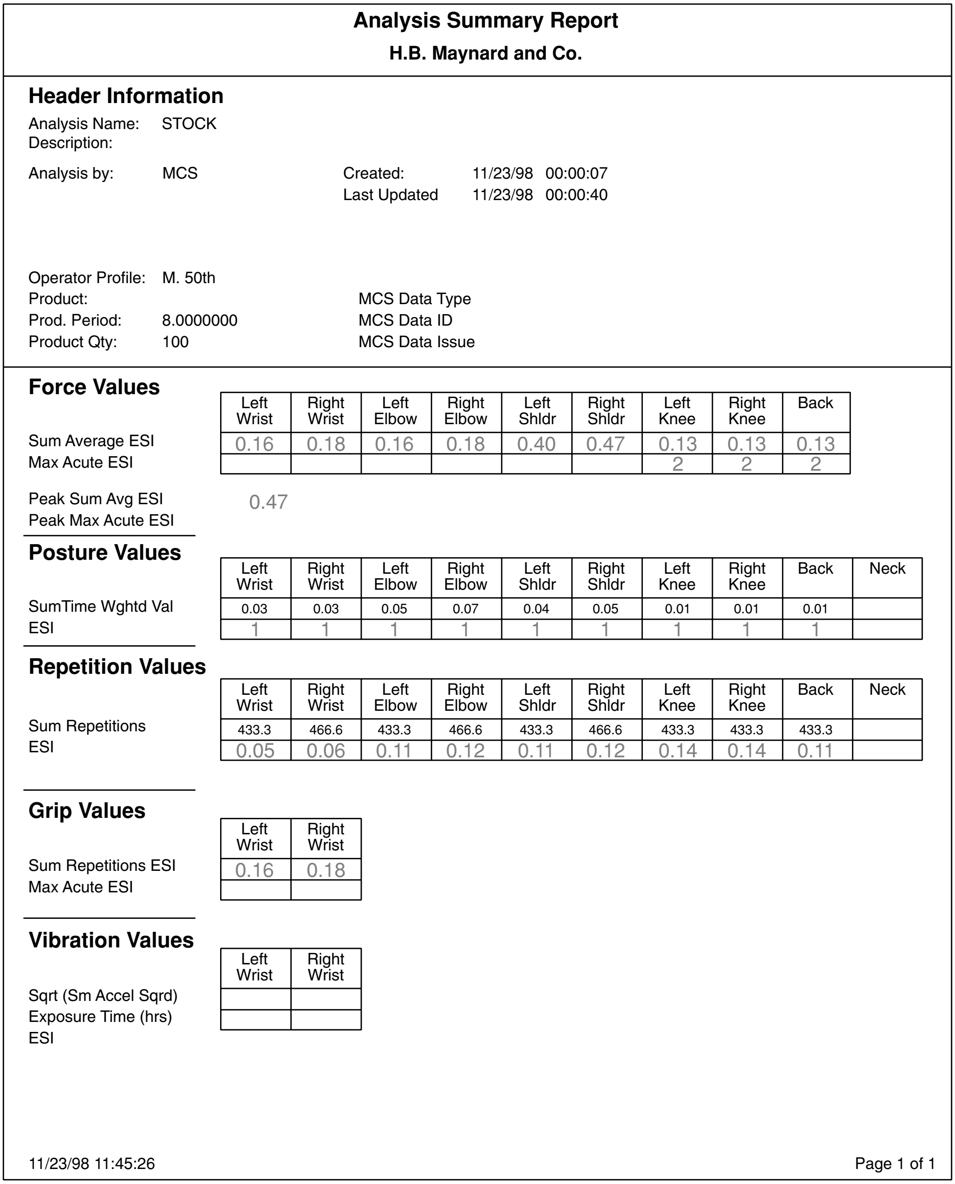
Figure 6.11.8 shows the input screen from the ErgoMOST Analysis using our example problem. Step 1 in the figure represents the action of getting a box from an incoming conveyor and moving it to the cart. The representative ErgoSet is displayed above the Method Description. Each step requires an ErgoSet or ergonomic information. The job information is then entered under the Header tab.

OUTPUT: After the information has been entered and saved, the ErgoMOST tool will then provide the evaluation of this job. The Analysis Summary output is a textual or graphical display of Ergonomic Stress Index (ESI) for each body member by ergonomic factors summarized for the whole job. The Ergonomic Stress Index is a five-point scoring system. These ratings indicate potential risk for each body member in the following manner:

1–2	low risk
3	medium risk
4–5	high risk

The goal of the system is to highlight higher risk methods so that the analyst can identify them and target them to be redesigned to reduce potential risk.

In Fig. 6.11.9 the Summary Report detailing the Force ESIs for each body member is shown. From this summary output, high Max Acute ESIs exist for the shoulders, knees, and back. These are the areas that can be investigated further by evaluating more detailed reports, such as the Top Methods of Concern and the Step Detail, which can be run to identify the methods in the job that have contributed the most to the high ESIs. From the information pro-



Analysis Summary Report

H.B. Maynard and Co.

Header Information

Analysis Name: STOCK
Description:

Analysis by: MCS
Created: 11/23/98 00:00:07
Last Updated 11/23/98 00:00:40

Operator Profile: M. 50th
Product:
Prod. Period: 8.0000000
Product Qty: 100

MCS Data Type
MCS Data ID
MCS Data Issue

Force Values

	Left Wrist	Right Wrist	Left Elbow	Right Elbow	Left Shldr	Right Shldr	Left Knee	Right Knee	Back
Sum Average ESI	0.16	0.18	0.16	0.18	0.40	0.47	0.13	0.13	0.13
Max Acute ESI							2	2	2

Peak Sum Avg ESI	0.47
Peak Max Acute ESI	

Posture Values

	Left Wrist	Right Wrist	Left Elbow	Right Elbow	Left Shldr	Right Shldr	Left Knee	Right Knee	Back	Neck
SumTime Wghtd Val	0.03	0.03	0.05	0.07	0.04	0.05	0.01	0.01	0.01	
ESI	1	1	1	1	1	1	1	1	1	

Repetition Values

	Left Wrist	Right Wrist	Left Elbow	Right Elbow	Left Shldr	Right Shldr	Left Knee	Right Knee	Back	Neck
Sum Repetitions	433.3	466.6	433.3	466.6	433.3	466.6	433.3	433.3	433.3	
ESI	0.05	0.06	0.11	0.12	0.11	0.12	0.14	0.14	0.11	

Grip Values

	Left Wrist	Right Wrist
Sum Repetitions ESI	0.16	0.18
Max Acute ESI		

Vibration Values

	Left Wrist	Right Wrist
Sqrt (Sm Accel Sqrd)		
Exposure Time (hrs)		
ESI		

11/23/98 11:45:26 Page 1 of 1

FIGURE 6.11.9 ErgoMOST output—text format.

vided on these reports, methods can be identified and redesigned to reduce the ergonomic risk associated with this job. The resulting job is then reevaluated by the ErgoMOST tool to verify the reduction in the ESIs.

A comparison of the original job and the revised job that eliminated most of the bending and extended reaching required to get and place the boxes is depicted in Fig. 6.11.10. From this comparison it can be seen that the ESI values for this job have been reduced.

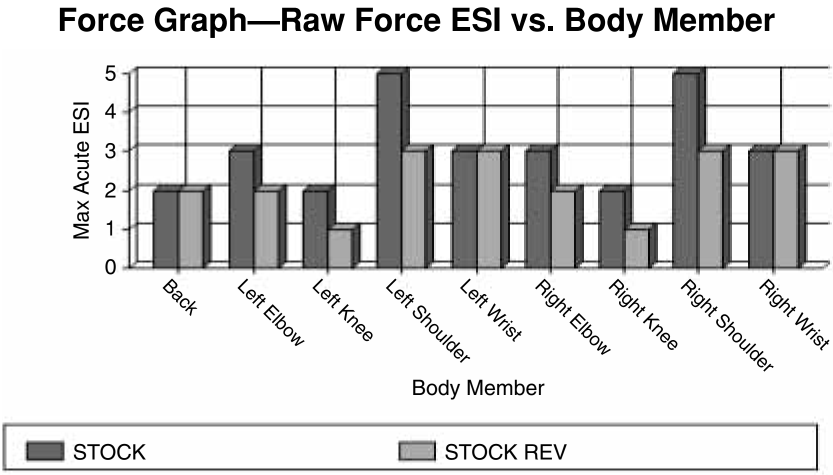


FIGURE 6.11.10 ErgoMOST output—graphical format.

Energy Expenditure Prediction Program—University of Michigan Center for Ergonomics. The energy expenditure analysis needs only to be performed if the worker

- Appears to be out of breath
- Is breathing heavily
- Is sweating
- Can't talk to you because they cannot keep up with the line rate

Energy expenditure equations have been developed for the following types of tasks:

- Walking—on level or inclined surface
- Lifts/lowers with following postures (stoop, squat, semisquat, one hand)
- Loads carried at waist or thigh level with one or both hands
- Loads held at waist or thighs, one or both hands
- Pushes and pulls at any height from the floor
- Handwork, light and heavy
- General arm work (light, less than 2.3 kg [5 lb] and heavy, more than 2.3 kg [5 lb])

Before you can start using the program, you need to break down the job task using the listed descriptions. Other inputs are weight of the worker, gender of the worker, and body postures with each task. The output of the program will provide incremental energy expenditure at every task and a total job energy expenditure of all the tasks. By analyzing the output, one can redesign tasks with the highest incremental energy expenditures to reduce the total energy expenditure. More information can be obtained from the University of Michigan Center for Ergonomics.

Recommendations

Table 6.11.7 is a summary of the results using all the tools in our example. From the summary we can see that four out of six tools indicate that we have a problem. Therefore, job redesign

TABLE 6.11.7 Summary of Results

IE ergonomic tools	Acceptable value	Actual example value	Action required
RULA	Score = 1	Score = 7	Redesign required
NIOSH 1991	RWL = 16.79	Weight = 25 lb	Redesign required
U. of M. 2D	90% female capable all joints	89% female hip capable	OK—no action required
Snook and Ciriello			
—push	initial 17 kg sust 10 kg	2.27 kg	OK—no action required
—pull	initial 17 kg sust 10 kg	2.27 kg	
ErgoMOST	ESI ≤ 3	ESI = 5 posture 5 force	Redesign required
U. of M. Energy Expenditure	5 kcal/min	8.73 kcal/min	Redesign required

is recommended. These same tools should be used to analyze different proposals to redesign this job and fix the ergonomic problem. By using the tools on a regular basis, you will be able to intuitively change specific factors on a job to give you a maximum improvement with minimum effort. In this example, if you change the height on the unload and load conveyors to about waist height, this will fix most of the ergonomic concerns.

All industrial engineers know about or have performed line balance traditionally based on work content established by standard data. We should apply the same approach to ergonomic analysis. This is nothing dramatic or new. Instead of using work content, use the ErgoMOST ESI or other quantitative ergonomic data to rebalance jobs and lower individual job ergonomic risks. For example, an individual may have an acceptable workload, but a high ergonomic stress load on the right elbow. Rebalance the right elbow work to reduce ergonomic stress at that job. This would be an efficient use of the ergonomic data available to the engineer and the line balancing concepts from traditional IE principles.

Documentation

In today's competitive market, companies are striving to achieve different levels of ISO [14] certification. This is one of many reasons to have a documented ergonomic process. If the first step in the ergonomic evaluation is to fill out the Job Design Data Collection Matrix, then it is important to control this document and have a central location for all records of evaluations. This documentation will prove to be beneficial if you have more than one analyst, and also give you the ability to correlate future injuries to job design parameters. To demonstrate a good process you need to document what you do, and do what you have stated in your documentation—3 Ds: Do, Document, Demonstrate.

CONCLUSION

Ergonomics as an applied science is difficult to grasp for most engineers. It is not an exact science such as math where $2 + 2 = 4$. In ergonomics, $2 + 2$ is an answer somewhere between 3 and 5 depending on many factors: person's height, weight, age, gender, and so on. Ergonomics is one of the few sciences that take these variables into consideration. In this chapter we have presented some practical tools to do a thorough ergonomic evaluation. The tools that you

ERGONOMIC EVALUATION TOOLS FOR ANALYZING WORK

should use are the ones that will give you similar answers independent of the analyst, and also correlate to your injury history. Ergonomics is a growing science with new information continually being made available. This is good reason to keep up to date, and one tool that will help is the Internet. University and government web sites are good places to start looking for this information.

ACKNOWLEDGMENTS

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BIOGRAPHIES

Damir (Dan) Cerovec, P.Eng., is a manager of the industrial engineering department at General Motors of Canada Ltd., Windsor Transmission Plant. His experience over the last 18 years has been in a number of different manufacturing environments. Prior to his current position, he held positions in industry as an industrial engineer, plant manager, process engineer, and a quality engineer. He holds a B.A.Sc. (industrial engineering) from the University of Windsor. He is a licensed Professional Engineer since 1986.

James Wilk is a senior account manager for H. B. Maynard and Company, Inc. His experience includes consulting for Maynard in various industries and implementing productivity improvement initiatives. He has been involved in the development of Maynard's ergonomic evaluation tools, in particular, ErgoMOST. He holds a B.S. in industrial and management systems engineering from Pennsylvania State University.

CHAPTER 6.12

CASE STUDIES: PREVENTION OF WORK-RELATED MUSCULOSKELETAL DISORDERS IN MANUFACTURING AND SERVICE ENVIRONMENTS

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The University of Pittsburgh
Pittsburgh, Pennsylvania

To adequately address ergonomic safety concerns in large organizations consisting of several hundred employees, the commitment of top management is essential. Such commitment involves the formation of company-supported ergonomics programs. These programs are proactive administrative bodies that regulate companywide changes in a controlled systematic manner. Their purpose is to help limit injuries and operating costs associated with musculoskeletal disorders found in the workplace. This chapter presents three case studies that describe ergonomic program initiatives in clothing manufacturing, grocery retail operations, and electronics manufacturing.

INTRODUCTION

When trying to prevent work-related musculoskeletal disorders (WRMSDs) in the workplace, one tool that can prove valuable to the industrial engineer are examples of successful intervention strategies. Such examples can provide the engineer with specific ideas concerning:

- Engineering controls that can reduce or eliminate risk factors associated with WRMSDs.
- Administrative changes that can enable an organization to effectively and proactively address the issue of WRMSDs in the workplace.

- Cost estimates that cover initial investment, operating expenses, and maintenance expenses for those implemented control measures.
- The benefits one can expect from ergonomic intervention and the time frame over which these benefits will be realized.

The purpose of this chapter is to describe in detail three case studies that document the requirements, procedures, and benefits of implementing ergonomics programs in the workplace. These case studies are a synopsis of three ergonomics site visits conducted by the U.S. Occupational Safety and Health Administration (OSHA). The details of each of these site visits were recorded by OSHA's Office of Regulatory Analysis (1993) to support the agency's proposed ergonomic protection standard. The cases will cover ergonomic improvements made in clothing manufacturing, grocery retail, and electronic component production.

CASE STUDY 1—CLOTHING MANUFACTURING

Background

The corporation produced men and boys sportswear including T-shirts, jerseys, sweat shirts, and sweat pants. Production was carried out through 18 apparel plants and 7 subsidiary facilities. The number of employees at each corporate site varied from 100 to 1000 employees. Review of employment records revealed that approximately 83 percent of the employees were engaged in clothing production while the remaining 17 percent worked in maintenance, management, and receiving/shipping departments. The production workers were compensated via a piecework incentive pay system. The corporate sites operated on a 40-hour workweek for production personnel, and a 47-hour workweek for maintenance employees. Employees could work overtime in some instances when sales demands warranted. The facilities owned by the corporation manufactured approximately 3,360,000 items of clothing per week. The corporation's annual net sales totaled approximately $800 million with after-tax earnings of over $56 million.

Objective and Scope

The corporation had decided that a large percentage of their occupational injuries and illnesses were attributable to WRMSDs. The corporate objective for intervention was to reduce by 50 percent those costs (i.e., workers' compensation, production loss, and insurance premiums) associated with WRMSDs. By the end of the fiscal year, the company had developed plans for an ergonomics management program designed to achieve this objective within a two-year period. This program would be implemented at all plants and subsidiary facilities. The plant selected as the prototype for the program employed 256 people. The activities performed by these employees were broken down into 10 categories (see Table 6.12.1). The ergonomics management program of the plant was based on the actions, and interaction, of two separate teams. The corporate ergonomics team was charged with the responsibility of designing and implementing the ergonomics program at the plant level.

Members of the corporate ergonomics team included a safety engineer, the corporate head of plant nursing (health care provider), and two industrial engineers. The corporate ergonomics team received quarterly reports from the plant ergonomics team. In addition, the corporate safety engineer received a weekly summary of recordable injuries incurred at the plant. Oversight of the program was the primary responsibility of the plant ergonomics team. This oversight entailed addressing complex plant issues as well as reporting plant activities to the

CASE STUDIES: PREVENTION OF WORK-RELATED MUSCULOSKELETAL DISORDERS
IN MANUFACTURING AND SERVICE ENVIRONMENTS

TABLE 6.12.1 Frequency Distribution of Jobs Held in Apparel Plant

Company position	Number of employees
Sewing machine operator	180
Folder/inspector	30
Packer	12
Receiving/distribution/shipping	10
Rework	6
Custodial	3
Clerical	1
Maintenance	4
Supervisor/trainer	8
Manager	2
Total	**256**

corporate ergonomics team. A total of 15 in-plant personnel composed the plant ergonomics team:

- Line supervisor
- Trainer
- Personnel manager (records team activities)
- Plant nurse
- Industrial engineer
- Maintenance workers
- Five to eight employee representatives

The team measured the performance of their program based on the number of recorded WRMSDs. Funding for the plant ergonomics team was covered as a part of plant expenses, integrated into the overall safety budget.

Program Procedure and Application

Both the corporate and plant ergonomics teams shared responsibility for the following five performance elements of the ergonomics program.

1. *Hazard identification.* This first function entailed identifying potential hazards associated with the development of WRMSDs. The corporate team's safety engineer reviewed the injury records submitted by the plant ergonomics team. When necessary, the corporate team would inform the plant's personnel manager that a potential hazard (i.e., problem job) may exist. Once notified of the situation, a plant team member would review the OSHA 200 logs of the operation, along with any employee reports concerning signs and symptoms associated with WRMSDs. In addition, the plant team also conducted a workplace walkthrough of the problem job. The walk-through required a plant team member to perform a 10-minute on-site observation of the potentially hazardous job. Once completed, the member engaged in a 20-minute discussion with the rest of the team. The purpose of this discussion is to select specific workers and tasks for ergonomic job hazard analysis. Over a period of 6 months, the plant ergonomics team had spent 29 person-hours conducting a total of 25 hazard identifications.

2. *Job hazard analysis.* The types of jobs that the plants ergonomics team targeted for job hazard analysis fell into one of three categories:

a. Those jobs that have been identified as having significant risk factors for WRMSDs, employee reports of problems/symptoms, or having a history of musculoskeletal injuries/illnesses

b. Those jobs that have recently been changed with regard to procedures, production processes, machinery, job location, or workers' responsibilities

c. New jobs or old jobs performed by new employees

Based on hazard identification, job analysis was focused primarily on the sewing machine operators, folders/inspectors, and rework personnel. The corporate ergonomics team carried out all hazard analyses whose results would affect all apparel facilities. The plant ergonomics team conducted analyses that impacted only its facility. The company used on-site observation by personnel trained in basic ergonomic principles along with videotape recording as the primary methods of analysis. Training in ergonomic data collection was provided by a university short course in ergonomics. The videotape recordings were used to analyze the workers' posture and identify those specific elements of the job that may have contributed to the development of injury/illness.

In addition, employee surveys were also administered to those workers in each targeted area. The surveys recorded information concerning comfort, risk factors, and potential solutions for problem jobs. Relevant findings of any previous time motion studies or job health analysis were also included in the current ergonomics evaluation. A final method of analysis employed by the corporation was employee ergonomics work groups. A group consists of workers trained in ergonomics who could analyze their own jobs and report their findings to the plant ergonomics team. The time required to perform the analysis varied from 30 minutes (for simple solutions resulting from in-plant analysis) to 20 working days for corporate investigations that resulted in changes implemented across all apparel facilities. Employee feedback concerning the effectiveness of changes was gathered by the company using postanalysis surveys and face-to-face interviews with affected employees.

The results and recommendations of all hazard analyses were documented in a written report. The plant ergonomics team would communicate the findings of each report to the affected employees. Within the first six months of the year, all 25 hazard identifications found in the sewing, inspection, and rework departments were analyzed (25 person-hours required). A simple solution to eliminate hazard exposure was found in each case. Table 6.12.2 summarizes the specific risk factors identified by these job hazard analyses. The solutions that addressed the risks outlined in Table 6.12.2 were developed and described under the third ergonomics program performance element, prevention and workplace modification.

3. *Prevention and workplace modification.* As part of the overall program, a combination of engineering controls, work practices, and administrative controls were used to eliminate (or substantially reduce) the risk factors described in Table 6.12.2. Engineering controls

TABLE 6.12.2 Specific WRMSD Risk Factors for Apparel Manufacture Operations

Ergonomic risk factors	Department location(s)	No. affected employees
Prolonged standing	Rework, folders/inspectors	33
Awkward sitting positions	Sewing, rework	183
Stooped posture and eye strain	Rework, folders/inspectors	33
Low back strain—carrying clothes bundles	Sewing, folders/inspectors	210
Working with bent wrists and elbows—attaching cuffs, waistbands	Sewing	35

(i.e., physical changes to the workstation) were considered to be the primary means of intervention in 75 to 80 percent of all task analyses conducted by the corporate ergonomics team. The engineering controls implemented affected 220 workstations and 216 workers in the sewing, rework, and folder/inspector departments. The implemented engineering controls included:

- Adjustable chairs to accommodate the varying heights of the sewing machine operators
- Vertically adjustable tables for folders/inspectors that allow for a 20° tilt in the table's surface
- Bundle trucks (i.e., carts) for transporting clothing between workstations
- Sewing machine attachments that permit more control and less handling of cloth used in cuffs and waistbands

A list of the specific controls and their costs are listed in Table 6.12.3.

The time required to implement the engineering controls listed in Table 6.12.3 would vary between a day, for relatively simple solutions, to more than a year for more complex modifications. The corporate ergonomics team monitored the effectiveness of all implemented engineering controls through the use of follow-up surveys, administered by the plant ergonomics team, to all affected employees. A comfort survey was administered to all affected employees prior to implementation of engineering controls. Approximately six months after implementation, these same employees were surveyed again. Results of the pre- and postcomfort surveys could then be compared for effectiveness evaluation purposes.

The plant also makes use of work practice controls in dealing with occupational risk factors that contribute to the development of WRMSDs. Each new employee received training from the plant's ergonomics team in the safe and proper work practices for their respective position. This training lasted 1 hour per day for the first 3 to 5 days of employment. When a job was altered, those affected employees would receive work practice training for 15 to 30 minutes. After implementation of the engineering controls, 180 sewing machine operators and 3 employees from rework received 15 minutes of work practice training. This training focused on the proper use of the new adjustable ergonomic chairs. After the cuffing and banding attachments were implemented, 35 affected employees received 30 minutes of work practice

TABLE 6.12.3 Engineering Control Measures for Clothing Manufacture Operation

		Cost categories		
Control measures	Risk factor addressed	Investment	Annual operating and maintenance	Annualized* investment plus operating and maintenance
Antifatigue floor matting	Constant standing	$ 3,300	$ 0	$ 1,327
Bundle trucks (carts)	Carrying clothes bundles	$ 500,000	$ 2,100	$ 83,500
Adjustable ergonomic chairs	Awkward sitting positions	$ 12,420	$ 0	$ 2,852
Vertically adjustable folding tables with tilting surface	Stooped posture/eye strain	$ 9,860	$ 0	$ 1,605
Cuffing and banding attachments	Working with bent wrists and elbows	$ 44,000	$ 1,200	$ 8,363
	Totals	$ 569,580	$ 3,300	$ 97,647

* Annualized investment cost over the life of the investment at a 10% interest rate.

training. This training was directed at the proper use of the new equipment that allowed for more control and less handling of the cloth when attaching cuffs and waistbands.

Several administrative controls were also implemented by the plant to support the objectives of the ergonomics program. The plant's ergonomics team established light duty jobs to be used by employees returning to work after injury or illness. Each piecework incentive pay job in the plant had a conditioning period provided for all new or transferred employees. This period allowed the employee to work at less than full production, gradually building up to expected productivity over time.

4. *Ergonomic medical management.* The ergonomic medical management program (EMMP) was established by the plant as a part of the overall health services provided by the facility. The plant nurse was placed in charge of EMMP and reports to the corporate ergonomics team through the head corporate nurse. The EMMP functions included developing light duty jobs for returning injured workers and conditioning periods for new or transferred employees. Before these employees were expected to be working at full production capability, members of the medical management department would monitor them weekly through the use of interviews, observations, and examinations. The medical management department also maintained records detailing employee complaints of discomfort, pain, or injuries associated with WRMSDs. Medical personnel spent 667 person-hours per year in the plants health services. Of that time, 40 percent was spent working on the EMMP.

5. *Ergonomics education and training.* Using university short courses, all members of the corporate ergonomics team received training in ergonomics principles. The team was then responsible for developing the format and presentation of training programs and materials for all corporate employees. The training focused on the following issues:

- The need for reporting, recording, and investigating injuries, illnesses and potential hazards associated with WRMSDs
- Symptoms and risk factors associated with WRMSDs
- Controls (engineering, work practice, and administrative) used to eliminate or reduce these risk factors
- Procedures for notifying management of potential hazards, symptoms, injuries, or ideas for hazard abatement
- Roles of the corporate ergonomics teams, plant ergonomics teams, and employee ergonomics work groups

Managers, supervisors/trainers, maintenance workers, and corporate-level engineers received four hours of ergonomics training. Hourly employees also received ergonomics instruction; however, their training was more example oriented with less detail. This training took approximately one hour. After initial training, each employee could expect a yearly follow-up session conducted by the plant ergonomics team. Within 12 months, 4100 employees received ergonomics training. Based on experience, company representatives estimated that a total investment of approximately $4000 was required to educate a 250-person plant.

Benefits of Ergonomic Intervention

The corporate ergonomics team evaluated the effectiveness of the plant's ergonomics program by monitoring the OSHA 200 logs over a three-year period. The total number of OSHA 200 reportable illnesses categorized as WRMSDs were recorded for each year, and are presented in Fig. 6.12.1.

By the end of year 3, plant representatives expected a 60 percent decrease in the number of OSHA 200 recordable illnesses associated with WRMSDs when compared with year 1. It

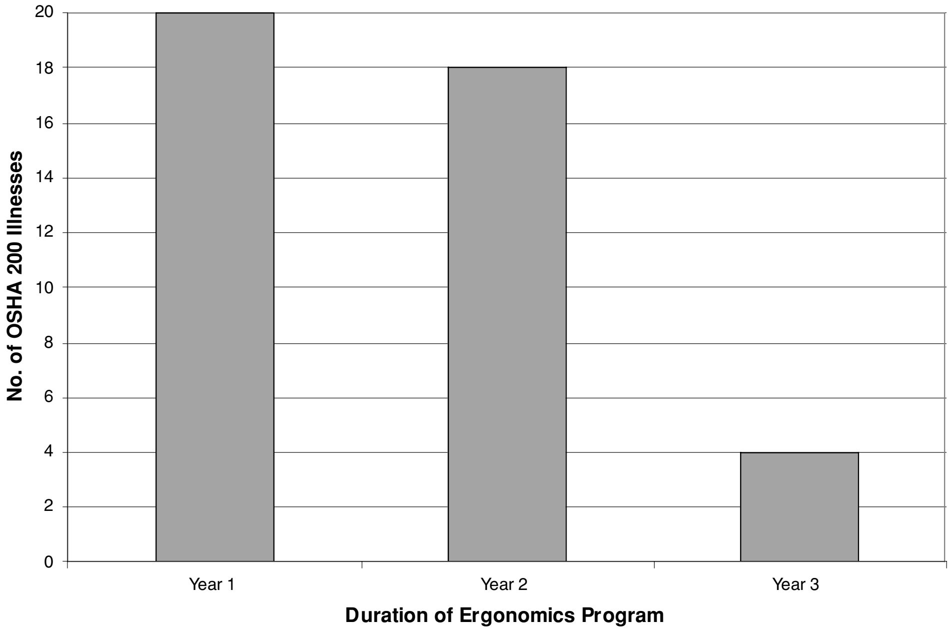

FIGURE 6.12.1 Number of WRMSDs recorded at clothing plant over a three-year period.

should be noted that total employment did not change significantly during this three-year period. From year 2 to year 3 the annualized illness incidence rate dropped from 7.17 per 100 employees to 3.13 per 100 employees, a decrease of 56 percent. Also in year 2 the plant had a lost-time frequency rate of 1.39 illnesses per 100 employees. As of year 3 no illnesses resulting in lost time had occurred. Productivity improvements were seen as well, especially with the bundle-trucks implementation, which resulted in an 8 percent labor savings. Plant representatives have also noted that the severity of ergonomic-related illnesses seemed to have decreased, and employee moral has increased during this period as employees began to participate in the ergonomics management program.

CASE STUDY 2—GROCERY RETAIL OPERATION

Background

The grocery retail operation selected for case study 2, was one of 71 stores held by a division of a nationwide supermarket chain. Most managerial decisions and support services were handled at the corporate/division level. Regional representatives were charged with the responsibility of carrying out corporate mandates and notifying the division as to what materials or services their stores may require.

The grocery store employed approximately 203 people. Six of these individuals were managers while the remaining 197 held positions as cashiers, stock clerks, and food preparers. The distribution of employees to store positions is shown in Table 6.12.4. Approximately 162 employees (80 percent) worked part-time, up to 30 hours per week. The employees worked staggered, irregular shifts of 6 to 8 hours in duration. These shifts occur during the store's hours of operation, which are 7 A.M. to midnight.

TABLE 6.12.4 Store Positions Held by 197 Grocery Store Employees

Store position	No. male employees	No. female employees	Total employees
Cashier/bagger	27	53	80
Stock clerk	43	9	52
Meat cutter	12	6	18
Produce clerk	5	6	11
Deli clerk	4	17	21
Baker	5	10	15
Total	**96**	**101**	**197**

Objective and Scope

The divisional staff of the supermarket chain made the determination that WRMSDs were becoming a serious safety issue according to OSHA, the National Institute for Occupational Safety and Health (NIOSH), and to the trade journals of their industry. In response to this growing concern, the division began their development of an ergonomics program. This program would address injuries and illnesses of the back and upper extremities of grocery store employees.

Following management approval, the division formulated and implemented a strategy for systematically resolving ergonomics-related problems in the workplace. This strategy possessed the following three key elements.

1. *A division committee on WRMSDs*—The purpose of this committee was to develop and execute an implementation plan. Members of the committee included representatives from claims administration, safety, retail operations, central purchasing, training, industrial engineering, and warehousing. The committee obtained its technical support in ergonomics through the use of an independent ergonomics consultant.
2. *An executive sponsor*—This individual was a division vice president. The role was to make presentations to corporate management with the purpose of obtaining top-level support for the ergonomics program.
3. *A continuous improvement approach*—This intervention policy stressed the importance of monitoring and finding long-term solutions, as opposed to applying "quick and dirty" fixes, to problem jobs.

With the exception of capital expenditures, ergonomics activities did not have a separate budget. Everyone's effort on behalf of the ergonomics committee was considered to be an integral part of his or her job responsibilities. Each year a budget was set for capital expenditures for replacement equipment and store retrofits. These capital expenditures were charged to individual stores as part of the distributed depreciation. Ergonomics-related costs were included in these expenditures.

Program Procedure and Application

Under the program, all ergonomics-related activities were overseen and coordinated by the division committee. Four individuals on this committee were charged with the primary responsibility of implementing the ergonomics program:

- Division director of retail operations
- Division director of claims administration and safety

- Division safety manager
- Division industrial engineer

These individuals also drafted the written portion of the corporation's ergonomics program. This document included the following sections:

- A detailed corporate strategy for dealing with WRMSDs
- Positional papers of each job category, which documented hazards, potential claims, solutions, and costs
- Tracking of WRMSD claims
- Quarterly updates and overviews of all activities related to WRMSDs

The committee stressed the achievement of certain strategic objectives, as opposed to quantitative goals, as the desired results of the ergonomics program. These objectives are expressed in the following five program elements.

1. *Hazard identification.* A systematic identification of hazards associated with all positions was carried out by the committee. Due to the uniformity of job responsibilities, hazard identification was not performed for each grocery store under the division. Members of the ergonomics committee, who conducted workplace walk-throughs at several representative stores, carried out initial hazard identification. Every walk-through entailed observing the activities associated with each job within the grocery store. The committee also frequently monitored those jobs currently undergoing ergonomic intervention to evaluate the impact of the changes. Reviews of claim records, reports of symptoms, employee surveys, and research journals were the alternative methods used by the committee to identify hazardous jobs. For each preliminary hazard identification, an independent ergonomics consultant was used to review and verify the findings of division staff personnel.

Each job was prioritized based on the severity of the ergonomics stressors and the number of workers involved. A job designated at level A would have the highest intervention priority, whereas level C jobs had lowest priority for intervention. Jobs with level B designation had an intermediate priority classification.

2. *Ergonomic job hazard analysis: positional papers.* Those jobs identified as possessing ergonomic hazards or associated with employee reports of complaints were subject to ergonomic job hazard analysis. An independent ergonomics consultant who (1) reviewed the initial hazard identification, (2) videotaped the jobs in question, (3) observed affected employees, and (4) identified the stresses to which these employees are exposed carries out this analysis. In a cooperative working arrangement with the division industrial engineer and the division safety manager, the ergonomics consultant drafted a positional paper for each ergonomic job hazard analysis. This paper contained the following information:

- Department, job title, physical activities, and employees at risk
- Priority rating for the job analyzed
- Detailed description of the problem
- Analysis of the potential and actual consequences of exposure to the hazard in question, along with the expected costs
- Findings of the analysis that determined potential solutions
- Action plan that listed those items necessary for solution evaluation and problem correction
- Costs of implementing the recommended solutions along with an implementation plan

To develop each positional paper, the industrial engineer, safety manager, and ergonomics consultant were called on to perform the following activities:

- Gather information on the problem from both inside and outside the company.
- Develop prototype specifications, review alternatives, and examine equipment under consideration for purchase.
- Conduct tests of proposed solutions.
- Push the project through management's approval process.

When specific changes had finally been determined and tested, the revised workplace design was accepted as a standard. With standard status, these changes were applied to all retrofits and new stores. Once the workplace had been modified, the jobs were observed and the affected employees are surveyed to gauge the effectiveness of the implemented changes. Table 6.12.5 summarizes the specific risk factors identified by job hazard analyses of grocery retail operations. The engineering and administrative controls developed to address these risk factors are discussed in the following section.

TABLE 6.12.5 Specific WRMSD Risk Factors for Grocery Retail Operation

Ergonomic risk factors	Department or position
Prolonged standing, repetitive handling of items, excessive reach distances, lifting items over scanner, inappropriate checkstand height	Cashiers
Constant repetitive bending, kneeling, and reaching while stacking items, lifting/carrying heavy items	Stock Clerks
Improper worktable height, wrapping meat by hand, bent wrist when cutting meat, prolonged periods of standing	Meat Department
Hand wrapping, bending, and reaching to stock tables, handling heavy objects, constant standing	Produce Department
Constant gripping when using slicer, twisting the back when transferring from slicer to scale, reaching over high counters to service customers, prolonged standing	Deli Department
Bent wrist, static grip forces, and awkward postures associated with cake decorating	Bakery Department

3. *Prevention and workplace modification.* A combination of engineering controls and work practices controls were used to eliminate (or substantially reduce) the risk factors described in Table 6.12.5. These controls were implemented as part of the overall ergonomics management program.

Since the start of the ergonomics program, 55 percent of all analyzed jobs have been modified via engineering or work practice controls. The time required for control implementation varied from immediate to approximately 10 months. The time needed depends on the type of testing done on proposed controls and the response of equipment vendors. In the program's first year, antifatigue matting was installed in the cashier, meat, and deli sections of the store. Over a 12-month period, the cashier checkstands were also modified. Specifically, these stands were converted from the traditional left-hand take-away design (where the left side of the cashier faces the customer) to a full-side scanning checkstand in which the cashier directly faces the customer. This change was implemented to reduce the required reaching distance and torso twisting of the cashier. In addition, new manually adjustable meat cutting tables were purchased for the meat department. The height and cutting surface angle of each table could be adjusted by the operator. Each new table also came equipped with a footrest that could be tilted up and out of the way when not in use. In addition, each table possessed a drip rail installed along the front edge of the cutting surface. This rail drained meat juices from the cutting surface. The elimination of these juices on the table surface decreased the manual force needed by the operator to cut the meat. In 1991, new knives were also ordered for the meat department. These knives were made of high-grade carbon steel and had bent handles that helped the operator maintain a straighter wrist when cutting. To keep the knives sharp, new sharpening equipment was installed at each meat workstation. Maintaining sharp knives helped reduce the manual force required by the operator. A list of the specific engineering controls and their costs are listed in Table 6.12.6.

In addition to engineering controls, the division also promoted safe work practices in response to observed ergonomic hazards. When jobs had been redesigned, all affected workers were trained in safe and proper work practices for their new jobs. This policy was followed when the new checkstands were installed in the cashier department. After implementation, cashiers were trained in the proper use of the new equipment.

4. *Medical management.* Each employee selected their own physician and/or health care facility. The company was responsible for the proper handling of all claims for medical costs and workers' compensation. The average medical claim costs for the division was about $500 per employee per year.

5. *Ergonomics education and training.* Management meetings were used to keep divisional, regional, and store managers informed as to all corporate plans to deal with WRMSDs. Labor relation meetings were conducted to discuss the activities of the ergonomics program with union representatives. Presentations by store managers, posters, pamphlets, and company newsletters informed employees about the basic workings of the ergonomics program. Line associates received only informal ergonomics training when their workstations were selected for modification. When an engineering control was considered for possible implementation, it was tested by a few employees in one or two locations. The employees then provided feedback to the divisional industrial engineer concerning the effectiveness of the proposed control. These same employees were also given reasons for implementation and instruction in the proper use of the new equipment. Division management, regional store managers, and individual store management received formal ergonomics training. This training course was prepared by members of the divisional committee and the independent ergonomics consultant. The course provided participants information as to what WRMSDs are, their importance in regard to daily operations, and what steps could be taken to reduce or

TABLE 6.12.6 Engineering Control Measures for Grocery Retail Operation

		Cost categories		
Control measures	Number of workers affected	Investment	Annual operating and maintenance	Annualized* investment plus operating and maintenance
Antifatigue floor matting at checkstands	71	$ 368	$ 0	$ 97
Modified checkstands	80	$ 26,445	$ 0	$ 6,976
Antifatigue floor matting in deli dept.	21	$ 222	$ 0	$ 59
Ergonomically designed meat knives	7	$ 378	–$ 928	– $ 850
Antifatigue floor matting in meat dept.	18	$ 412	$ 0	$ 109
Modified meat cutting tables	18	$ 5,600	$ 560	$ 2,037
	Totals	$ 33,435.00	–$ 368	$ 8,428

* Costs preceded by a negative sign represent cost savings.
† Annualized investment cost over the life of the investment at a 10% interest rate.

eliminate them. In the initial training course, the director of claim administration and safety provided an assessment of the impact that WRMSDs have on the business and stressed the need for an ergonomics management program. The ergonomics consultant then discussed:

- Basic principles of human anatomy
- The ergonomic risk factors of WRMSDs
- Specific jobs and the hazards associated with them
- Solutions for reducing or eliminating ergonomic risk factors

The training session took approximately 2.5 hours to complete. The ergonomics training for the division industrial engineer and the safety manager was somewhat more intensive, requiring a four-day university course in ergonomics. In addition, these two individuals would also attend ergonomics workshops, conferences, and seminars periodically throughout the year. Included in their training would be visits and discussions with ergonomics experts for the grocery industry and with equipment vendors.

Benefits of Ergonomic Intervention

The benefits of the ergonomics management program were assessed by surveying the medical claims for all 71 stores in the division. The data included those injuries and illnesses associated with WRMSDs and excluded back injuries. These costs are summarized in Table 6.12.7.

The total cost of WRMSD claims for all 71 stores decreased approximately 60 percent over a three-year period. The average cost of a WRMSD claim decreased approximately 66 percent from year 1 to year 2. Finally the percentage of all medical claims associated with WRMSDs dropped from 11.5 percent in year 1 to only 4.9 percent in year 3. One should note that from year 1 to year 2 the number of WRMSD claims more than doubled. This increase may be attributed to increased employee awareness due to the educational component of the ergonomics management program. On a divisionwide basis, the ergonomics committee concluded that as a result of the ergonomics management program, there was a substantial decrease in medical cost claims associated with WRMSDs. Employee complaints also decreased and employee morale greatly improved.

CASE STUDY 3—ELECTRONIC COMPONENT MANUFACTURING

Background

This facility produced electronic engine controls, temperature control sensors, mechanical speed controls, and universal electronic spark controls for automobiles. At the time of the site visit, the plant employed 2277 people. Figure 6.12.2 shows the number of people employed in each of the facilities departments. The distribution of employees to plant positions is shown in Table 6.12.8. The average age of employees in this facility is 43 years.

TABLE 6.12.7 WRMSD Medical Claim Costs for Grocery Retail Operations

Year	Employees in division	Number WRMSD claims	Total cost of WRMSD claims	Average cost of WRMSD claims	WRMSD costs as a proportion of all claim costs
1	8905	22	$ 566,000	$ 25,700	11.5%
2	8825	48	$ 415,000	$ 8,700	8.5%
3	9043	26	$ 225,000	$ 8,700	4.9%

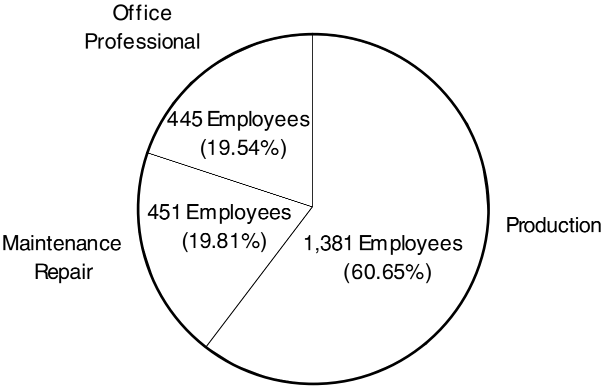

FIGURE 6.12.2 Number of employees at electronics facility.

The plant was one of eight other facilities owned and operated by a corporation. Each plant employed anywhere from 800 to 5000 employees. These facilities were all contained under the corporation's ergonomics management program.

TABLE 6.12.8 Plant Positions Held by 2277 Employees

Store position	No. male employees	No. female employees	Total employees
Assemblers	286	427	713
Material handlers	115	28	143
Misc. production	210	315	525
Maintenance	432	13	445
Professional	225	226	451
Total	**1268**	**1009**	**2277**

The plant operated on a three-shift, five-day workweek. During the first shift (12 A.M. to 7 A.M.), janitorial and maintenance activities were performed. The second shift ran from 7 A.M. to 3:30 P.M. while the third shift ran from 3:30 P.M. to 12 A.M. Engine control units were the primary unit of product manufactured at the facility. The production rate was approximately 10,700 units a day. Annual sales are approximately $500 million, based on the plant's published estimates.

Objective and Scope

The plant received an OSHA citation for ergonomics violations. In response to this citation, the facility implemented an ergonomics program. The program was reflective of a larger corporate initiative to reduce the incidence of injuries and illnesses, workers' compensation costs, and insurance costs for all eight facilities. Plant management had set a goal of reducing the lost workdays due to WRMSDs by 25 percent over a 12-month period coupled with another 25 percent reduction over the next 12 months. Funding for the ergonomics program was provided through a budget allocated for training purposes.

Program Procedure and Application

The ergonomics program developed by the facility was proactive in the sense that efforts were made in the initial design of new equipment and products to prevent ergonomic hazards from occurring. The implementation and oversight of the ergonomics program at the plant was the responsibility of the local ergonomics committee (LEC). The LEC comprised 14 members who held the following plant positions:

- Plant nurses
- Production employees
- Human resource personnel
- Health and safety personnel
- Engineers
- Top-ranking union member at the plant
- Plant manager

The plant manager and union official acted as the cochairs of the LEC. The LEC was made aware of potential ergonomic hazards from the work groups located in the plant. Work groups were small teams of production workers (6 to 11 members) that strived to achieve their production objectives established by management. One of their functions was to discuss any pertinent health and safety issues (such as ergonomics) that affect their work area and report such concerns to the LEC. These work groups also made recommendations to the engineer members of the LEC, who used these ideas to develop solutions. The LEC investigated all feasible solutions and reported its findings to all affected workers. Outside support was made available to the LEC through consulting firms that provided ergonomics training and analyzed hazardous jobs in the plant. Medical health specialists were used for proper diagnosis of employee WRMSDs. Finally, insurers specializing in return-to-work processes assisted managers in determining the functional capabilities and return-to-work dates of injured workers. The plant's ergonomics program relied on several principle documents to support its primary functions:

- The corporate manual of ergonomics
- A guide for proper documentation of ergonomics activities
- A concern log that documented ergonomic hazards from initial identification through solution implementation and follow-up
- An evidence book that documented the activities of the LEC, its current projects, and its past accomplishments

The functions of the LEC are outlined using the five following program elements:

1. *Hazard identification.* In the first year of the ergonomics program, formal identification of ergonomic hazards began at the plant. The primary responsibility for identifying potential hazards fell to the LEC. Although members of the LEC engage in hazard identification, members of the work groups also participated, reporting their findings to the LEC. The following methods were used by plant personnel to identify potential ergonomic hazards:

- Examining injury and medical records, searching for trends
- Direct observation of hazards through the use of workplace walk-throughs
- Monitoring employee reports of signs/symptoms associated with WRMSDs
- Reviewing medical examinations looking for employees in job classifications with ergonomic risk factors
- Review of scientific literature on ergonomic hazards associated with specific manufacturing processes

- Running the results of ergonomics checklists on newly installed equipment
- Analyzing the results of preemployment screening and placement surveys

Approximately 1 person-hour was required to perform hazard identification. The number of hazard identifications increased steadily over a three-year period. By the end of the first year, a total of 65 hazard identifications were made by the LEC. These identifications focused on 90 workstations within the plant and affected 115 workers. By the end of the second year, a total of 108 additional hazard identifications were made by the LEC. These identifications focused on 130 workstations within the plant and affected 250 workers. Through October of the third year, the LEC had compiled 130 instances of potential ergonomic hazards. These hazards involved 170 workstations and affected 290 workers.

2. *Ergonomic job hazard analysis.* Job hazard analysis was performed by members of the LEC on those jobs identified as possessing potential ergonomic hazards. New jobs and altered jobs were subjected to analysis, as well. The plant made use of various methods for ergonomic hazard analysis:

- Elemental task analysis
- Postural analysis
- Computerized biomechanical analysis
- Ergonomics surveys
- Job safety analyses (JSA)
- Time and motion studies

Analysis was carried out through the use of either direct observation or videotape review, usually requiring 1 to 2 hours to complete. The purpose of using these various methods was to measure the rate of repetition, magnitude, and duration of ergonomic hazard exposure. These measurements could then be used to prioritize jobs for ergonomic intervention. To assist in the analyses, employee work groups were trained to evaluate the physical stressors of their own jobs, relaying their concerns and suggestions to the LEC. This type of employee involvement increased worker awareness of ergonomics issues.

During the first year of the ergonomics program, the LEC conducted approximately 65 job analyses involving 90 workstations and affecting 115 employees. The LEC's effort required 65 hours for analysis plus 100 additional hours to discuss the findings and possible solutions. In the second year, 108 jobs were analyzed requiring 836 hours of analysis and solution formulation. For the third year, the LEC had conducted a total of 130 job analyses affecting 290 workers. These analyses revealed that the positions in assembly, material handling, and maintenance were associated with a high risk of WRMSDs. The physical stressors for each of these plant positions are listed in Table 6.12.9.

3. *Prevention and workplace modification.* The plant made use of engineering, work practices, and administrative controls to address the risk factors found in the assembly, material handling, and maintenance departments. The time requirements for implementation varied from one day to an entire year depending on the complexity of the problem. The effectiveness of intervention was measured by the LEC by surveying the affected employees and by receiving feedback from the various work groups. The following engineering controls were applied to problems found in the assembly, material handling, and maintenance departments:

- Redesigned electronic components for easier assembly
- Adjustable worktables and chairs
- Redesigned pneumatic hand tools and presses for maintenance
- A pneumatic snap tool allowing for easier installation of units
- Vacuum hoists, unloading lifts, and air jacks to reduce lifting

TABLE 6.12.9 Specific WRMSD Risk Factors for Electronics Manufacturing Operation

Ergonomic risk factors	Department location
Repetitive handling of parts, using force to install parts, repetitive twisting and bending of the wrist, static muscle loading, sustained tilting of the neck and upper back when working, low back strain due to prolonged sitting	Assembly
Performing heavy lifting while the back is bent or twisted, forceful pushing and pulling	Material handling
Prolonged elevation of the arms, working with hands and arms above shoulder level, repetitive application of manual force, contact stresses on the hands and wrists, frequent twisting and bending of the wrists, elbows, and shoulders, lifting and carrying heavy objects, pushing and pulling with force, working in posture that requires back bending and twisting while exerting force	Maintenance

- Computerized supply cell transporters for assembly and handling
- A new hydraulic automatic brake machine in maintenance that requires less force to operate than the original (manually operated)

In addition to modifying the plant floor departments, office workers received ergonomically designed office furniture in the first year of the ergonomics program, even though they were considered to be at low risk for WRMSDs. Administrative controls were also applied to the problem. Employees involved in material handling were rotated with those workers who performed packaging and inspection to allow for variation in the load weight and frequency of handling. Light duty jobs were also developed to assist workers who were returning from previous injury or illness. Work practice controls included training in safe and proper work practices for new hires, as well as those employees whose job responsibilities had recently changed. Table 6.12.10 provides a summary of the costs for control measures implemented over a three-year period.

TABLE 6.12.10 Control Measures for Electronics Assembly Operation

	Cost categories		
Department(s)	Investment	Annual operating and maintenance	Annualized* investment plus operating and maintenance
Assembly Material handling Misc. production	$ 1,750,000	$ 175,000	$ 636,650
Maintenance	$ 62,000	$ 6,200	$ 22,560
Office/clerical engineering	$ 331,000	$ 0	$ 87,320
Totals	$ 2,143,000	$ 181,200	$ 746,530

* Annualized investment cost over the life of the investment at a 10% interest rate.

4. *Medical management.* The plant's medical management program included all employees. During the first year of the program, the company hired a full-time physician, four nurses, and a physical therapist, all of whom are available on-site. Members of the medical management program conduct preemployment screening, job placement interviews, and physicals. Medical surveillance was also conducted for those employees working in jobs where ergonomic risk factors were suspected to be present. Those employees returning to work after injury or illness were evaluated by medical management to determine what their specific capabilities were and what restrictions should be placed on their work activity. The annual effort of the plant's medical management program was approximately 7.5 person-years with 25 percent of this time spent on ergonomics-related issues.

5. *Employee education and training.* In-house staff, the corporate office, and outside consultants all participated in the development of the ergonomics training courses and materials for the plant. All plant employees received ergonomics training. The plant provided four different levels of ergonomics training:

a. The corporate ergonomist provided all members of the LEC with 4.5 hours of ergonomics instruction in 1990. Training included definitions, risk factors, controls, and documentation practices. Every two years, the LEC was to receive a one-day refresher course.

b. The LEC administered a two-day training course on ergonomics to 200 plant engineers. Training covered the correct design of workstations, equipment, and tools. This training was provided during the second and third year of the program to ensure that all new engineers received ergonomics instruction.

c. An outside consultant provided 300 material handlers and maintenance personnel a two-hour back-training course. Topics covered included an overview of biomechanics, proper lifting techniques, symptoms, and treatment of back injuries. Each worker received an annual refresher course.

d. In the third year of the program, all production workers and new employees received a one hour ergonomics overview from an outside consultant. The purpose of this training was to increase workers awareness of ergonomic safety concerns and teach them how to participate in the ergonomics management program. The main concepts of this training were reinforced with weekly safety talks.

Benefits of Ergonomic Intervention

To assess the impact of the plant's ergonomics management program, the incidence and severity rates of WRMSDs were recorded over a three-year period and summarized in Table 6.12.11. From year 1 to year 2 there was a 51 percent decrease in the incidence of WRMSDs throughout the plant. By year 3, this rate had decreased again by 33 percent although part of this decrease may be attributable to the decrease in total employees. The severity rate (i.e., number of lost-time work days) had also decreased over the three-year period. From year 1 to

TABLE 6.12.11 Incidence and Severity Rates for WRMSDs for Electronics Plant

Year	Employees	Incidence rate per 100 employees	Severity rate per 100 employees
1	2800	37	116
2	2800	18	58
3	2277	12	29

year 2 there was a 50 percent decrease in the severity of WRMSDs throughout the plant. By year 3, this rate had decreased again by another 50 percent. Members of the LEC reported that these drops in injury incidence and severity were coupled with increases in employee morale.

CONCLUSIONS

A point clearly illustrated by the previous three case studies is that the role of the industrial engineer in ergonomics interventions is one of practitioner, teacher, *and* team leader. Reduction in the incidence of WRMSDs is possible through the coordinated effort of the plant engineers, supervisors, health care providers, and shop floor–level employees. In addition to reduced numbers of injuries, the implementation of ergonomics management programs was associated with increases in worker productivity and morale. These changes (reduced operating costs and increased efficiency) demonstrate how ergonomic intervention can be economically beneficial to manufacturing and service organizations. Future research in ergonomics management programs should focus on (1) documenting the specific program characteristics of those organizations that are successful in reducing WRMSDs among their employees, and (2) comparing and contrasting the program functions of large corporations and small businesses. This information will assist the engineer in developing an effective proactive administrative mechanism to adequately address ergonomics-related issues in various work environments.

BIOGRAPHIES

Brian Carnahan received his doctorate in industrial engineering at the University of Pittsburgh. This degree is added to his B.S. in science from the Pennsylvania State University and master's in industrial engineering and operations research from the University of Massachusetts. He has worked extensively as an industrial engineer and ergonomist for the U.S. Department of Labor's Occupational Safety and Health Administration (OSHA) in Washington, DC. In addition, he has held a position as a human factors specialist for the Carnegie Mellon Research Group in Pittsburgh and CMU's Driver Training and Safety Institute. He has also acted as an instructor in industrial ergonomics for Pitt's Department of Industrial Engineering and in applied mathematics for the university's Manufacturing Assistance Center. Currently, Carnahan is an assistant professor in the Industrial and Systems Engineering Department at Auburn University. His research interests have focused primarily upon developing artificial intelligence applications to help solve challenging problems in ergonomics, safety, and health. These applications have focused on the automated design of safe lifting tasks, industrial job rotation scheduling, assembly line balancing, low back injury risk modeling, and skill and accident analyses of long haulage truck drivers. Carnahan is a member of the Human Factors and Ergonomics Society, The Industrial Ergonomics Technical Group, The Institute of Industrial Engineers, The American Society for Safety Engineers, and the Alpha Pi Mu Society.

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SECTION 7

COMPENSATION MANAGEMENT AND LABOR RELATIONS

CHAPTER 7.1

PERFORMANCE-BASED COMPENSATION: DESIGNING TOTAL REWARDS TO DRIVE PERFORMANCE

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This chapter explores the concept of total compensation and how to use compensation to dramatically improve performance. Each component of total compensation is first defined, and then analyzed with case studies to show how each component is evolving. The design basics for each are presented, as well as when some types of compensation are more appropriate. The chapter concludes with a look at how rewards will evolve. How will the employer-employee contract change in the twenty-first century, and how will it impact each component of total rewards?

TOTAL REWARDS DEFINED

Overview

Over the last few decades, American companies have endured (and survived) a difficult period during which world markets evolved and produced new competitors while traditional consumer and industrial demand flagged. American companies went back to the drawing boards to reinvent themselves. They shrank, they reengineered, they developed a process focus, and they implemented broad technological solutions. The concept of competition changed, as did the concept of markets. The result has been the most dynamic economy seen in this country in a generation and a new emphasis on process improvement and change. Through such trials, organizations have come to realize that effective enterprise change cannot happen with a workforce that is not up to the task. It became clear that to make it all work, a dedicated, inventive, and dynamic workforce was needed. Achieving success with change demands an effective workforce. As a result, human resources including compensation has moved towards the center stage as a source of ideas and tools to ensure that an effective workforce is achieved. Successful companies, therefore, think strategically about compensation:

- Every dollar spent on compensation is held accountable for its contributions to the operation's performance.
- Every dollar spent on compensation is treated as an investment in the continued success of the organization.

Total compensation includes the following four components:

1. *Base pay level*
   Base pay is the amount of cash compensation paid on a regular basis (pay period). It is generally a measure of a position's worth to the organization given the duties its incumbents carry out and the competitive wage rate for that work in the external labor market.
2. *Base pay progression*
   Base pay progression defines movement of base pay over time. Traditionally, increases are based on longevity with the company and merit, but increasingly, it is based on the acquisition of business-related skills and competencies.
3. *Variable pay*
   Variable pay is cash compensation that does not roll into base pay. Variable pay is generally based on some measure of performance, either an individual measure, a team measure, or an organizational measure.
4. *Benefits and indirect compensation*
   Benefits and indirect compensation are less tangible forms of compensation that companies offer, such as insurance or flexible hours. Although this is not cash that goes into an employee's pocket, these can have just as strong an effect, and a successful total compensation package will consider benefits and indirect compensation an equally integrated component of total rewards.

Taken together, the components of total rewards offer organizational leadership a powerful "toolbox" for motivating and developing the workforce into an industry leader. Companies that have been successful in compensation strategy have worked long and hard to develop their compensation packages. Gone are the days when pay was a cost of doing business: today, it is considered an investment in organizational performance.

The case of an electronics company start-up illustrates how effective total compensation strategy can drive performance. The company established a new center for manufacturing a broad line of consumer electronics products in the early 1990s. The plant's mission was to become the world's leading supplier of products in the market. Management decided on the following strategies to achieve this mission:

- The plant would be based on high involvement principles.
- The workforce would work in teams.
- The manufacturing processes would be based on continuous improvement.

The start-up site represented a particular challenge because of its location in an area characterized by failed start-ups and labor-management conflicts. How did this company escape the ghosts in their new location that threatened a successful start-up? A major step involved taking a strategic look at total rewards.

Base Pay Level

The company designed base pay to accomplish primarily attraction and retention, particularly for highly skilled employees. The objective was to ensure a stable workforce.

Base Pay Progression

A skill-based pay program was implemented. As employees grew skills that were relevant to the manufacturing process, they could expect pay to grow to a target rate representing fair pay for a fully qualified process operator/technician. To encourage team development and cohesiveness, half of the pay steps were based on mastery and practice of team skills. The requirement ensured that the workforce grew both the technical *and* team skills that the company needed.

Variable Pay

To encourage continuous improvement, a variable pay plan called GoalSharing was implemented. GoalSharing provided additional pay as incentive for achieving continuous improvement on key process metrics (the "dials on the dashboard"). GoalSharing resulted in employee teams focused on constantly improving the key measures of the business.

Benefits and Indirect Compensation

The company provided a competitive level of benefits (health, disability, pension, and savings plan). Beyond these elements, however, the most important element of indirect compensation was the working environment defining the plant's culture. It was an opportunity to be associated with a respected, growing company and to work on teams. Empowerment provided the freedom to aggressively pursue performance goals and ensured that the plant would become an employer of choice in the area.

Taking the time up front to develop a total rewards strategy ensured that compensation would contribute to a successful start-up. Today, almost a decade later, the plant is widely benchmarked as a best practice. The facility has high-involvement teams, with very low turnover and higher levels of labor productivity.

Every year in the new economy, stories like this one are increasingly common as companies base their success on strategically designed total rewards. Enlightened approaches to total rewards have been the key to the newfound strength of American companies, and will be the basis for American competitive advantage in the twenty-first century. In this chapter, we will focus in-depth on each component of compensation and how rewards are changing in today's workplace.

BASE PAY

Definition

Base pay is generally the core of any compensation strategy, and provides the foundation for total rewards. It consists of the cash compensation that is delivered on a recurring basis to the employee for his or her position. It is the hourly wage or monthly salary paid. Traditionally, base pay was seen as an entitlement that goes with the position or job one occupies; however, more recent approaches have raised expectations for base pay.

Traditional Base Pay

The traditional role of base pay is to provide a wage or salary to an employee that is competitive with the external labor market. The employee derived all of his or her income from base pay, and base pay determined the living standard. Base pay was dependable and predictable.

Traditionally, base pay has been associated with putting one's time in: "Another day, another dollar" or the Japanese "salary man" of the 1980s.

What we have just described is an industrial model of base pay. Central to this view is the importance of the job as a way of thinking about work and pay. Under traditional model, one pays the job, not the person. People are considered interchangeable parts—if someone leaves, find a replacement. The industrial model is driven by the job. Job sets boundaries for work—if it is not in my job description, I do not do it. Jobs are turf.

The economic and technological forces of the 1980s and 1990s has forced a postindustrial model of work that places the job in a less prominent position. A process discipline, for example, forces people to work in far greater depth and breadth—beyond the confines of a traditional job. The focus has shifted from the job to the person. Thus, base pay is more focused on rewarding the person for the capacity he or she has to contribute than the job he or she occupies.

Postindustrial Base Pay

In the postindustrial model, base pay serves two objectives:

1. Attract key talent.
2. Retain key talent.

Traditionally, base pay was administered using two tools: job evaluation and salary grades. Job evaluation, often using points to represent job value, was used to rate a job. Job evaluation suffers from two shortcomings in the postindustrial era:

1. Job evaluation misses the mark of estimating a person's worth to an entire business process because it still focuses on jobs that do not align with processes. In a process-oriented world, value is not created by holding a job but one's personal capability to perform an entire business process.
2. Point factor job evaluation typically does not take into account roles on a team. As companies have moved to teams, they have found that traditional job evaluation systems become irrelevant because they missed much of the value-adding activities associated with cross-training and flexibility. In addition, job evaluation methods add a level of complexity in analysis that is not necessary when pay is tied to the person rather than the job.

Companies that have been successful with business process redesign, enterprise resource planning (ERP), and team-based work structure have realized that they have to look at base pay differently as well. In the past decade, there has been a move towards wider, simpler pay bands, known as broad-banding, and person-based methods for valuing work, both of which are based directly on market value and bypass job evaluation technology completely. A broad band gives a manager the flexibility to grow the workforce that will best serve the organization, not just move them directly into narrow, functional "silos."

The experience of an apparel manufacturer illustrates how base pay is changing. The company implemented ERP to automate and streamline the material purchasing process. The decision had serious implications for how people were paid. Prior to ERP, purchasing had been divided into very clear, delineated jobs, each specializing in a type of material, from buttons to zippers to thread to fabric. Employees in these jobs were paid to become increasingly specialized in their jobs: building relationships with vendors, knowing who to contact in a pinch, and so on. The degree of job specialization lead to two dysfunctions:

1. Purchasing was very prone to "crunches" for any given type of material. Temporary employees would have to be hired to support the specialist in one type of material while

other purchasing specialists had little or nothing to do. The cost of having to hire temporary employees was becoming significant, particularly since large customers insisted on having more variety in less time.

2. When a purchasing specialist left, all of his or her contacts and experience left as well, leaving the organization scrambling to acquire appropriate material at an acceptable price *on time.*

ERP was implemented to automate the interaction with vendors, make the company less dependent on single-person relationships, and make the activities involved in the purchasing process uniform and efficient across all types of material. The new technology, however, could not work unless people acquired new skills and adapted to new roles that took them beyond their prior job descriptions. Base pay systems needed to send the right message about ERP and reward people for growing into their new role.

Purchasing specialists, for example, were now expected to grow their skills laterally, across material types, instead of specializing in one type of material. This would make the workforce more flexible (so fewer temporary employees would have to be hired) and knowledgeable (so the organization was less impacted by one person leaving). The traditional system of salary grades, however, paid for depth, not for breadth. Broader pay bands were adopted to accommodate higher levels of base pay that reflected the greater breadth and depth of skills for which employees would be held accountable in their new roles.

The result was a workforce that grew into a more cohesive team, covering crises as needed and ensuring that the company not only saw a return on investment for compensation paid, but also a return on the investment in ERP because it was being used effectively.

BASE PAY PROGRESSION

Traditional Base Pay Progression

Traditionally, base pay progression has been based on three factors:

1. *Time in grade*
   Many companies grant across-the-board cost-of-living increases (usually annually) to reflect external economic inflation. Very little strategy is applied; base pay progression is viewed as cost to be minimized.
2. *Merit*
   In practice, merit systems have proved to be of modest success because of the difficulty of managing fairness in relation to inflation in external markets and worker merit simultaneously. The result has been modest, at best, pay distribution based on merit.
3. *Promotion*
   More recently, firms have attempted to make all or part of an award contingent on an individual's performance appraisal. Called a merit system, its purpose is to reward superior performance. In contrast to time in grade and merit, promotion increases are tied to a change in job assignment. Reflecting higher level responsibilities, the employee is moved to a higher pay grade.

As development of the workforce is increasingly seen as a strategic tool for organizations, alternative methods of base pay progression have been developed. Older methods of merit and promotion did not reflect new development goals, and as a result, base pay progression based on individual and team development has become increasingly prevalent. New models for base pay progression are becoming prominent in redesigned, new, or growing organizations:

- Skill-based pay
- Competency-based pay

Skill-Based Pay

Skill-based pay is a policy that rewards employees for acquiring and using work-related skills. The origins of skill-based pay can be found in the skilled trades, a system in which a new person began by studying under a master as an apprentice. Once the training was complete, the tradesman was certified as a journeyman, capable of working independently.

Skill-based pay generally specifies a sequence of skill blocks (grouping of activities) that must be mastered to be fully qualified in one's work. For each skill block accomplished, the employee's pay increases until he or she achieves the target rate for a fully qualified person.

It is important to remember that a skill-based pay system *will increase labor cost.* As an employee grows the skills that make the organization successful, that person's worth to the company improves as well. The hard-nosed cost-benefit question that has to be asked is, "What are we getting for these higher rates?" The business case must be made for skill-based pay. Skill-based pay systems have proved attractive to companies that have undergone business process transformations. New business processes require employees to orient away from narrow functionally centered jobs to broad roles that cover entire business processes.

Successful skill-based pay programs start with a focus on the process. Such a focus develops a very clear vision for how the workforce needs to develop to make the organization successful. It may be that a traditional workplace with functional silos is the best way to develop the workforce, or it may be that a flat, multiskilled workforce is the best way to achieve the organization's goals. The point is that by looking at the process first, it is possible to determine *for certain* what activities will carry the most value for the organization, and then fit your workforce around the most valuable activities.

The experience of a call center illustrates the potential impact of skill-based pay. The call center recently used skill-based pay to respond to a challenge given to them by corporate management. The call center was part of a catalog company that offered a wide range of products. Recently, customers had complained about long wait times and being transferred frequently in order to get questions about products answered. In response, the senior management decided that the company *must* be seen as the number one customer service organization. To accomplish this, the call center had to ensure the following:

- All calls were answered quickly.
- The same person who picked up the phone answered all questions.

This presented a challenge for the call center because the length of calls and the number of times a customer had to be transferred were related to the customer service representative's (CSR) lack of knowledge of such wide array of products. Often a CSR would be experienced in one type of product, but as soon as a question was asked about a different type of product, the CSR would have to transfer the caller (and potential customer) to the expert who may or may not be available.

The company recognized that all CSRs needed a basic grounding in the spectrum of products that the company offered, but for truly complicated inquiries, experts would be needed. It was impossible for all CSRs to be experts in everything, so how could a structure be developed that would reflect both the need for experts and the basics?

The company met this challenge with skill-based pay. Call center management developed a matrix that included the key product types as columns and the level of technical expertise as rows. The matrix consisted of a series of skill blocks. A skill block, then, defines various levels (entry to advanced) of technical knowledge for a variety of products. Asking employees to master the skill blocks ensured that all products were covered and that customer service would be optimized.

As a second step, the company identified career paths, which are the combination of skill blocks that a CSR was expected to learn. Each CSR was required to learn the basics for each product class (the Entry level). Then a CSR would become an expert in a product class (the Accomplished and Advanced levels, in this case).

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As the CSR mastered skill blocks—either at the Entry level in other product classes or Accomplished/Advanced in the home product class, the CSR received a pay increase. To get the raise, the CSR has to show that he or she had mastered *all* of the components of the skill block: knowledge, activity, *and* result. This ensured that training was being applied (and having an impact).

The call center now had a structured approach to developing workforce. Skill-based pay provided a training road map for each person, and for the workforce. The result was that every dollar spent on training and on compensation could clearly be demonstrated to have an impact on the organization.

Skill-based pay is not simply pay for knowledge. The method must be built on a foundation of three components: (1) knowledge, (2) activity, and (3) result. By certifying all three of these components, the skill-based pay system ensures that the skills being acquired are important to the organization, are being used, and are allowing employees to achieve the required results. This approach works very well when the activities and the results are distinguishable at a micro level and recur with reasonable frequency, but what about people who apply technical expertise daily in a wide variety of situations or who work on a variety of different projects? As knowledge-based work has become more prevalent, a different approach is often employed.

Competency-Based Pay

Competency-based pay differs from skill-based pay in that it is based on broad competencies rather than narrow, task-related skills. A competency-based system reinforces the specific technical and professional knowledge required to perform in a broad technical or professional capacity. Examples of competency-based pay include engineering and technical organizations where employees are expected to apply highly intellectual capacities to complete knowledge work.

An aerospace company's experience presents a good example of competency-based pay. The company opened a plant where success would hinge on a team environment that was structured using competency-based pay. The work design for this company was particularly critical because Federal Aviation Administration (FAA) regulations dictated process. In addition, the plant was to be certified by the International Organization for Standardization (ISO).

The company designed competency-based pay for its technicians. The plan was based on knowledge and process improvement—an approach that focused less on the actual work done and more on intellectual capital. As the plant began to produce airplanes, process improvement and intellectual capital formed the basis of the teams and of the culture. Over time, quality and process performance improved as a direct result of the development and application of key competencies.

The results were clear. Sales increased dramatically, with each plane literally flying out the door to a happy customer. Years later, we were working with a state university and mentioned this case. A person in the group stopped us and mentioned that they had recently purchased a number of these planes specifically because the sales force had demonstrated to them how building the planes in a team environment had made the planes safer and less expensive.

Competency-based and skill-based pay share the same goals and characteristics. Both do not depend on time on the job or seniority or promotions to increase pay. Instead, they depend on the employee developing into a strong asset for the organization. The more value the employee delivers to the organization, the higher the base pay the employee can expect.

Hence, the programs are effective tools for developing a workforce. Pay for skills or competency assures that the right capacities will be in place when needed. What about paying for performance? We will explore this issue further under variable pay.

VARIABLE PAY

Resurgence in Variable Pay

Variable pay is compensation that is nonrecurring (i.e., does not roll into base pay). Variable pay can be independent of performance, such as a holiday bonus, or can be linked directly to the performance of the individual, team, or organization. Although simple variable pay plans have been relatively common for decades, there has been a resurgence of interest in variable pay plans in recent years. Companies have found that performance can be significantly increased through the use of variable pay incentives. Indeed most successful variable pay plans have produced performance that broke through performance ceilings that had been elusive in the past.

We have found that companies considering alternative rewards often look first at variable pay for three reasons:

1. Variable pay may make compensation cost more manageable by relating it to ability to pay.
2. Variable pay provides an opportunity to link pay to performance.
3. Variable pay provides an opportunity or platform to teach the business, encourage interest in the business, and create line of sight between individual/group efforts and business results.

Variable pay is a complement—not a substitute—for skill- or competency-based pay. The latter represents an investment in skill development—which is long term. Variable pay, in contrast, pays for performance in each period. If performance is there, pay is there. If performance is not there, pay is not. Pay/performance contingency provides a strong incentive to achieve performance goals.

Traditional Variable Pay

Traditionally, participation in variable pay programs has been restricted to executive, managerial, and sales employees. More recently, variable pay has been extended to broader groups of employees. Following is our analysis of the three most common broad-based employee incentive programs.

1. *Profit Sharing* Still the most common form of variable pay, profit sharing returns a share of financial profit of a company to employees. The share can be determined by management discretion or according to a formula.

The advantages of profit sharing are twofold. First, it is simple, deriving from a single overall measure of the business. Second, it is affordable. If there is no profit, there is no payment.

The major disadvantage of profit sharing is that many employees lack sufficient understanding of core economics of their employer's business. Therefore, they do not have a sense that their efforts influence profit. The result is that a profit sharing payment is not seen as something earned for performance but as an entitlement.

2. *Individual Variable Pay* Individual variable pay plans include lump sum bonuses, productivity-based programs like piece rates and suggestion systems. Individual plans have the advantage of focusing on individual effort and are clearly appropriate when work is under the employee's control and independent of the work of others. Individual variable pay plans do not work when team efforts and coordination are required.

3. *Group Variable Pay* As work has become more process-oriented, teams have become an increasingly attractive and common way of organizing efforts. So, too, have group variable pay plans that reward an entire group of employees or teams for achieving results.

Perhaps the most prominent group plans are called *gainsharing.* Such plans date to the 1930s and share the following features:

- Simple measures—usually cost or productivity.
- Historical standards—set by a cost-accounting or industrial engineering staff.
- Participation—limited to shop floor, direct employees.
- No sunsets—plans are not updated as business needs change.

Technological events of recent years have rendered gainsharing, as just described, obsolete. Operating environments of the 1990s require firms to perform on multiple performance dimensions. In addition, the distinction between line and staff, direct and indirect has disappeared as high-performance teams have become the norm.

Group plans have evolved into a type of program called *GoalSharing*. The plans are based on business performance and share the following characteristics in contrast to gainsharing:

- Measures address three or four key performance areas (e.g., cost, productivity, quality, and customer service).
- Goals are set by making forward-looking business judgments and are not dictated by historical data.
- Participation goes "wall to wall" embracing all employees to reflect a team culture.
- The plans have sunsets operating year to year with a requirement to revise, renew, and evolve the program as the business grows and changes.

Making Variable Pay Successful

In order for GoalSharing (or any other program) to be successful five things must happen:

1. The plan gets attention and generates excitement.
2. The plan is understood.
3. The plan increases focus on the business.
4. The plan operates as designed.
5. The plan contributes to improvement in business performance.

Successful Design of Variable Pay

Recently, new approaches in variable pay design have created significant successes in performance improvement. Innovative approaches such as GoalSharing have lead companies to dramatically increase performance by simply focusing the workforce on one set of goals—the *key* goals of the business.

A food processing plant faced with a difficult problem provides a good example of GoalSharing. The plant was facing intense competition both in the market and between other plants in the company. If the facility was going to improve performance, it needed to focus the entire workforce on key performance improvement areas. Plant management chose GoalSharing to accomplish this result. The challenge, however, was to develop a plan that could be cost justified.

Management tasked a design team made up of a cross section of plant employees to ensure that the plan would be well received by the workforce. The design team followed these steps:

1. They first decided in what general areas the facility must be successful. They determined that these critical success factors were cost, quality, and customer service.

2. They built a “balanced scorecard” by identifying the business’s critical success factors and candidate measures. Five criteria were used to determine if a measure was acceptable:
   - **a.** Can it easily be measured?
   - **b.** Can it easily be communicated?
   - **c.** Does it impact business performance?
   - **d.** Does it make the process run better?
   - **e.** Does it reinforce the vision for the workforce?
3. Once each measure was established, it was weighted based on its importance.
4. Performance levels were established that reflected process improvement:
   - **a.** Threshold: The lowest level of performance, beneath which no payout is made. Often this is last year’s performance.
   - **b.** Target: This is the expected level of performance. If the workforce is focused on performance, this goal is 80 to 90 percent attainable.
   - **c.** Stretch: This is best-in-class or better performance. Generally, with substantial effort, this goal is 50 to 60 percent attainable.
5. An annual review process was instituted to ensure that the GoalSharing plan remained “evergreen” year after year.
6. Finally, the design team focused substantial effort of communicating the plan to all employees. This included:
   - **a.** A company picnic
   - **b.** Cards and other material with GoalSharing measure information
   - **c.** Brightly colored billboards in the plant tracking performance on an ongoing basis

Generating this focus yielded remarkable performance increases for the plant. Today, the plant is considered the best performer in the corporation and is used by other company plants as the model for using variable pay to achieve breakthrough results.

As the example shows, variable pay has extended beyond executive compensation and sales incentives to include a broad range of employees. Variable pay plans have also evolved in terms of design, role in total compensation, and focus. The factors that make a variable pay program successful, however, have remained constant. Research has shown that 38 percent of incentive programs fail because [1]:

- They end up as entitlements.
- They end up as a source of contention between management and labor.
- They fade away and leave a bitter taste.

Successful Implementation of Variable Pay

Why such a high failure rate? Looking at companies that have experienced failed compensation programs shows that they generally did not fail because of flawed design, but because of *flawed execution.* The single most common, and unfortunately most crucial, mistake that companies make is investing the best minds and the most effort on designing the plan, then failing to devote the same attention to execution.

Having a flawed execution traps companies because the damage done to the perception of the plan is very difficult to reverse. The causes of a flawed execution are generally because of

- Not being ready
- Not communicating eloquently or enough

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- Not involving employees in goal-setting
- Not being able to assess the impact of the program and change its direction

These are generally avoidable mistakes, but it means going against the first impulse in variable pay design: focusing all effort on the tangible plan design. If the plan is poorly communicated, if the workforce does not understand the plan, or if the workforce does not care about the plan, then no matter how well it is designed, it will fail.

Successful Management of Variable Pay

Since organizations will change substantially over time, it is reasonable to assume that performance expectations will change over time. Some measures may become less important, while others become more important. Many times, the obsolete variable pay plan is left behind. The plan is not changed, its goals become irrelevant, and the payout has little or nothing to do with organizational performance.

This is particularly true when considering continuous improvement. A company will implement a variable pay plan that helps the business improve. After two or three years, higher levels of performance are required, but the variable pay plan stays the same. The plan starts paying for performance that is not helping the organization compete any better; the payout becomes so regular that it is considered part of base pay—it's a given. The company designs a new variable pay plan to achieve the new performance objectives, and the cycle repeats itself until the organization has a basket of variable pay plans that are confusing and benefit the company very little, if at all.

If a variable pay plan is going to be successful in the long run, it *must* be evaluated on an annual basis to make sure that it is achieving its objectives.

Variable pay provides a very good example of how innovative companies are thinking about compensation. By rewarding for process improvement, it is possible for the organization to spend fewer resources overall for improvement. The payback in terms of process performance improvement outweighs any additional dollars paid in the form of variable incentive pay.

BENEFITS AND INDIRECT COMPENSATION

A Dynamic Component of Total Rewards

In the spectrum of total rewards, the most dynamic and most talked about compensation tools in recent years are benefits and indirect compensation (sometimes known as recognition). In the past, these were generally thought of as perks that were strictly limited to the employee's position on the organizational hierarchy. Today, benefits and recognition extend to all employees.

Total Rewards and Diversity

As the employee population has grown more diverse in the last two decades, the workforce's expectations regarding what they seek in the form of rewards has become varied. Recognizing the need to customize rewards to match the diversity of employee needs has brought benefits and indirect compensation to the forefront of alternative rewards. Companies thinking strategically about compensation today offer flexibility, key benefits, and different office environments to employees to make them more satisfied and productive.

The result is that the use of benefits has increased substantially since the 1950s [2]. The categories of employees to whom benefits are offered have expanded significantly as well. It is very normal to find 401Ks in union contracts, health benefits and discounts offered to employees at multiple levels, and a variety of personal financial management packages for all employees.

Rewarding with Benefits

The motivation for offering increased benefits to a wider segment of the workforce has changed as well. Traditionally, benefits were a reward for loyalty—congratulations for longevity with the employer. Today, the message sent is completely different: benefits are a joint accountability of the employer and employee. Examples of this trend in benefits included the shift from defined benefits to defined contribution pension plans, co-pay on health insurance, and the premise of 401K plans.

New benefit plans also offer employees the option to pick and choose benefits and perks that fit their lifestyles and let them more seamlessly incorporate work into their lives. In a flexible and diverse workforce, allowing employees some choice in designing their own package makes sure that the link between pay and performance and pay and perceived incentive is strong.

The importance of this link will only continue to grow as the workforce in the next twenty years becomes younger, more diverse, and more flexible. People entering the workforce today entertain very few ideas about being with one company for their entire career. Instead, people are planning their careers by determining how they want to grow their skills, what kind of lifestyle they want to have, and how flexible they want to be. Alternative rewards in benefits and indirect compensation are an excellent way to reflect this change and ensure that no matter how diverse the workforce is, everyone has the same incentive to perform.

Indeed, in the future, the use of benefits and indirect compensation will increase substantially not only in terms of the portion of the workforce to whom they are offered but also in terms of the percent of total compensation. This is because the economy has changed fundamentally: the employee-employer contract has been rewritten and has forced compensation to be seen in a strategic light. The next step is to define this new implicit contract between employers and employees and how that will impact total compensation. In short, to define the "New Deal."

THE NEW DEAL

Organizations and Employees

The trends in alternative compensation that we have examined in this chapter are part of a broader restructuring of the underlying relationship between organizations and employees. How employer and employee interact and what they expect from each other we call the *New Deal.* The New Deal is

- Flexible: Employees have varied work schedules and may work away from the office.
- Performance-based: Each employee is expected to have an ongoing impact on the organization.
- Technology-driven: E-mail, the Internet, and the Web all are part of work.
- Based on assignment: Lifetime employment is no guarantee. Employment will last only as long as the business need.
- Responsible: It is up to the employee to develop and change.

To many people, these points sound scary, but it opens a breadth of opportunity never before open to the workforce. Employees in today's economy can expect adequate reward for the fruits of their labor; if they do not get it, they will leave. Technology has given people tremendous freedom to work where and when they want, allowing time for family, recreation, and work.

The workforce will grow into a diverse mixture of working styles, ideas, and concepts. They will look for ways to develop themselves and will expect appropriate rewards. This throws down the gauntlet for effective compensation design. It is clear that compensation will never look the same again.

The New Deal and Base Pay

Base pay will remain an important component of total compensation in the New Deal. Its basis will shift from the job one occupies to the skills one brings to the table. In addition, the relative importance of base pay in the total compensation mix will shift down somewhat, as the importance of variable pay increases.

The New Deal and Base Pay Progression

In the New Deal, pay succession will increasingly be focused on the expectation that an employee will be focused on developing *and applying* skills that have a clear impact on the organization. As impact increases, pay increases. The days of significant base pay raises based solely on longevity are over.

The New Deal and Variable Pay

Pay for performance is the mantra of the New Deal. Variable pay will be pervasive in total compensation packages, and as a percent of total compensation will continue to grow. Employees will see opportunities to increase gross income *substantially,* while employers will continue to break performance ceilings by providing the right incentives.

The New Deal and Benefits and Indirect Compensation

Benefits will become a shared accountability in the New Deal. In addition, employees will see more individual choices in benefits and working arrangements.

It has been argued that alternative rewards are a double-edged sword because money only comes with performance. It has also been argued that alternative rewards are a key driver of recent economic growth because being strategic about compensation dollars grows performance at the team, organizational, and national level, which in turn creates more wealth and improves the economy even further. No matter what the point of view, it is clear that there is a New Deal in compensation, in human resources, and in the economy as a whole.

Understanding all the components of total compensation, and taking the time to align every component, opens up incredible possibilities for everyone. Employers are ready. Employees are ready. It is time for the New Deal.

BIOGRAPHIES

Marc J. Wallace, **Jr.**, is a founding partner of the Center for Workforce Effectiveness. He is based in Northbrook, Illinois, where he serves as a management consultant specializing in workforce effectiveness, human resource strategy, and compensation. Prior to founding the

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center in 1992, he was professor and Ashland Oil Fellow in the Department of Management, College of Business and Economics, University of Kentucky. He holds the B.A. degree from Cornell University and the M.A. and Ph.D. degrees in industrial relations from the University of Minnesota.

Marc John Wallace III is a project manager at the Center for Workforce Effectiveness. Prior to joining CWE in 1995, he graduated from Thunderbird in Glendale, Arizona, with a master's of international management. He has also received a B.A. from the University of Wisconsin in economics and certification in social and economic administration from the Faculté d'Économie Appliquée (Université d'Aix-Marseille) in Aix-en-Provence, France. Since joining CWE, Wallace has worked extensively with companies to design a wide variety of work and rewards strategies including variable pay, skill-based pay, partnership (union/management) agreements, and labor market analyses.

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CHAPTER 7.2

JOB EVALUATION

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This chapter is designed to aid the reader in understanding the design and application of point-factor job evaluation plans. The majority of organizations employing formal job evaluation use point-factor plans. After a brief history of the evolution of job evaluation and a discussion of basic principles, the article discusses design considerations and application rules. The application rules that are included are valuable aids for anyone using either a customized or off-the-shelf job evaluation system.

The conclusion of this chapter postulates that without a suitable replacement technique, job evaluation has a solid future and should be thoroughly understood by all of those who are involved with wage administration.

> *Ideally, employees should be paid according to the nature of the job they perform and its value in relation to other jobs in the organization for which they work. The external competitiveness of a company's wage structure is also an important factor in its pay policies, since it must continue to attract and retain qualified applicants in a competitive employment market.*
>
> *Establishing job values and internal pay differentials is one of the most important challenges an organization must face in developing and administering its pay plan. The larger the organization, the more important consistency and fairness are to the rules of job structuring and wage allocation among the many departments. The more people doing the same or similar tasks, the greater the demand for "equal pay for equal work." The more difficult, strenuous, or tedious the work tasks or conditions, the more employees will expect a reward for their efforts.*
>
> —An introduction by George J. Matkov, Attorney at Law, Matkov, Salzman, Madoff & Gunn, Chicago, Illinois

INTRODUCTION

All organizations require a structure or framework to determine what work must be accomplished and by whom. Organizations establish this internal structure either informally or with a formal approach called *job evaluation.* Estimates suggest that over 95 percent of the major U.S. corporations use job evaluation to develop the internal wage structure [1]. Job evaluation is the process of converting job content and job responsibilities into a rationale for a job hierarchy. Job evaluation is not an end in itself; it is one of four interrelated steps involved in an objective approach to pay structure design. These four steps are as follows:

1. Job analysis and preparation of job descriptions
2. Job evaluation by analyzing each job description using a formal technique
3. Wage surveys to understand the external marketplace
4. Pay structure development and equitable pay delivery

Step 2, the job evaluation, the topic of this article, has four requirements.

1. *Accurate inputs.* Updated job descriptions are essential inputs to job evaluation. The unique requirements and content of each job must be determined, documented, and understood. This is a two-stage process requiring job analysis and the preparation of job descriptions.
   - ***a.*** During job analysis, information is gathered by interview, observation, questionnaire, or diary in two broad areas: job tasks and required skills of job holders. Job analysis is the foundation for the entire job evaluation process with the object to develop an accurate and concise job description that can be used to evaluate the contents and value of that job.
   - ***b.*** A job description should be a brief summary of the essential duties and responsibilities of the job and generally includes five or six sections.
     - **(1)** An identification section stating job title, department, plant, status (exempt/nonexempt), and a wage rate.
     - **(2)** A summary statement that identifies the overall function of the job and its major activities.
     - **(3)** The source of supervision. Describe supervision received and the type of supervision, if any, provided by the jobholder.
     - **(4)** A listing of the principal job duties. These are stated in order of importance or frequency of performance. Normally, about 10 to 12 principle duties are sufficient.
     - **(5)** The minimum requirements for entry into the job in terms of training, education, experience, and skills.
     - **(6)** The normal working conditions associated with the job.

   Job descriptions must be developed with legal considerations in mind. Descriptions must be in compliance with federal and state nondiscrimination laws and the Americans with Disabilities Act of 1990.
2. *The need for skilled job analysts and evaluators.* For each job to be studied, the analyst must conduct a detailed review of the work requirements, responsibility levels, educational and training requirements, and work environment. Detailed questionnaires are typically used to gather this data. The data gathered is verified and synthesized into a short, one-page job description. A committee of job evaluators is formed to evaluate each position using an evaluation tool. It is important that individuals involved in job evaluation are sufficiently familiar with each job under review. This knowledge will enable them to make the necessary comparisons of job content and job requirements down to a level or degree of a specific factor.
3. *A formal job evaluation methodology.* The method(s) selected depends on the composition of the group(s) being evaluated, the scope of jobs to be included, union considerations, and overall wage administration policy. The methodology must include an evaluation manual with a rule set and instructions.

4. *Job evaluation requires a holistic approach.* Pay structures must be developed that reflect organization pay policy and a desired relationship with relevant external labor markets. When developing a pay policy, all components of the compensation and reward system must be considered. Job evaluation cannot be the only criterion used to establish final pay levels. Additionally, it is essential to consider economic conditions, labor markets, unique skill availability, collective-bargaining issues, and other related matters when deciding the final pay levels of jobs.

This article will focus on job evaluation principles, the most common techniques used today, and a shop-floor installation model using the point-factor job evaluation method.

PRINCIPLES OF JOB EVALUATION

Job evaluation systems that are in use today are all based on the following three fundamental principles:

1. Job evaluation establishes the relative, rather than the absolute, value of jobs.
2. It is the job, rather than the person doing the job, that is being evaluated.
3. The results of a job evaluation procedure are just one consideration in the determination of the appropriate wage rate for a particular job or class of jobs.

WHY USE JOB EVALUATION?

A job evaluation program is usually considered by an organization when one or more of the following circumstances exist [2]:

- Generalized internal dissatisfaction and frequent disputes have arisen concerning the wage structure, including claims that similar work does not result in equal pay, that equal pay is given for dissimilar work, or that differences in pay are not related to the work performed.
- There is concern that certain groups of workers (such as women) are being underpaid as the result of unlawful discrimination.
- New equipment or new methods of work have been introduced that change the content of many jobs, resulting in the need for establishing a new basis for remunerating those workers who have been affected.
- Organizational changes (such as a business consolidation) have been made that necessitate a revision of the wage system.
- Changes in the nature of the company's work, machines, production methods, or products have left an unmanageable number of job descriptions to administer.
- The business plan of the organization calls for changes in resource allocation and labor cost management.
- New pay delivery vehicles (such as pay-for-performance, gainsharing, or other performance incentives) are being introduced that require that a sound base-pay structure be in place.
- A high employee turnover rate and growing number of unsuccessful recruitment attempts indicate that better-paying employment opportunities are being offered elsewhere in the industry or area.

The decision to embark on a job evaluation program must be made at the top level of the organization, and receive full support of its chief executives and the on-site management team.

JOB EVALUATION HISTORY

Job evaluation is not new. As early as 1871, the U.S. Civil Service Commission adopted a rough form of evaluation that consisted of merely classifying jobs. The Classification Act of 1923 (Public Law 67-516) was the true beginning of the federal job classification and pay system, authorizing the U.S. Civil Service Commission to centrally classify all "headquarters" white-collar positions. From this stemmed the Classification Act of 1949 (Public Law 81-248), which authorized the Commission to develop classification standards and establish the General Schedule of 18 pay grades for all covered federal employees. The General Schedule (GS) system is founded on the principle of "equal pay for substantially equal work" and pay variations "in proportion to substantial differences in the difficulty, responsibility, and qualification requirements of the work performed" (U.S. Code 1976:5101).

The point-factor plans had their beginning in 1937 when the National Electric Manufacturing Association (NEMA) introduced the program entitled "NEMA Job Rating Plan for Hourly Rated Jobs," which was soon followed with a similar plan for office jobs. Today, under a variety of names, point-factor programs still enjoy widespread use in the United States and abroad. Both the original NEMA plan, which was not copyrighted, and the similar National Metal Trades Association (NMTA) plan are still in use.

Over the years there has been an uneven adoption of job evaluation programs. It is difficult to find uniform acceptance of job evaluation within any one industry. One exception is the basic steel industry where, in 1944, the Cooperative Wage Study (CWS) project began. The resulting 12-factor CWS plan was the product of a joint management-union cooperative effort to standardize job evaluations throughout the basic steel industry. What the CWS did was to develop an industry-wide job evaluation plan for all production and maintenance jobs and nonconfidential clerical jobs. The CWS and modified CWS-type plans continue to be used today. The United Steelworkers of America, the AFL-CIO-CLC, and the Coordinating Committee Steel Companies completed the most recent update to the CWS *Job Description and Classification Manual* in August of 1971 [3].

The Hay Guide-Chart Profile Method is a modification and simplification of early factor comparison methods. The system has been refined over a 30-year period by Edward N. Hay and Associates. The Hay Guide-Chart Profile Method is frequently used for the evaluation of managerial and professional jobs. This system compares jobs with respect to three factors that are common to all jobs: (1) know-how, (2) problem solving, and (3) accountability. Each of these three factors is further divided into several subfactors, and a matrix or guide chart is developed.

In the late 1940s, compensation professionals began to develop an interest in market pricing of jobs. The market pricing approach to job evaluation moves the focus of the process from within the organization (internal equity) to an external perspective. Market pricing systems were developed to recognize the realities of the marketplace as the primary focus with a secondary focus placed on internal equity.

Use of job evaluation is not universal. The lack of acceptance and adoption of job evaluation plans has roots in both management and labor. Those in management who are opposed to job evaluation cite the adequacy of the present wage structure while financial and cultural conversion costs also act as inhibitors to change. Some believe that job evaluation systems install too much rigidity into a workplace that is constantly seeking flexibility in its workforce. Others feel job evaluation systems that focus only on the "value of the job" rather than on the "value of the person's skill performing the job" go against modern reward-and-recognition theory.

Union opposition to job evaluation, which was strong initially, has shown signs of reversing. Union leaders had fears that job evaluation would lead to the elimination of individual rate

JOB EVALUATION

negotiations and weaken job security. However, over the years, many unions have adapted their position on job evaluation, recognizing its ability to support and preserve job security.

GLOSSARY OF TERMS

Before beginning a more detailed discussion of the various job evaluation systems, it is important to define commonly used job evaluation terms.

Benchmark jobs (key jobs). Benchmark jobs provide a basis for inter- and intraorganizational comparisons because they occur in several organizational elements, are similar in content, and are detailed in standard terms. Other jobs are compared as being above, below, or comparable with the benchmark jobs.

Compensable factor. A compensable factor is the basic criterion used to determine the relative worth of jobs. Compensable factors consist of attributes that, in the judgment of management, constitute the basis for establishing relative worth; examples include knowledge, skill, training, experience, accountability, responsibility, and working conditions [4].

Effort. The measurement of physical or mental exertion needed for the performance of a job.

Job. According to the American Compensation Association, a job is "the total collection of tasks, duties, and responsibilities assigned to one or more individuals whose work has the same nature and level" [5]. *Note:* Although a job may be a composite of the work done by more than one individual, the analyst should always treat a job as being done by a single worker to discount individual abilities and performance.

Position. The total work assignment of an individual employee. The total number of positions in an organization always equals the number of employees and vacancies. Analysis based on positions is undesirable because two or more positions might have the same or very similar descriptions.

Responsibility. The extent to which an employer depends on the employee to do the job as expected, with emphasis on the importance of job obligation.

Skill. The U.S. Department of Labor defines *skill* as the experience, training, education, and ability that are required to do a job under consideration. Skill as used in job evaluation relates to the skill requirements of the job not the skill of the employee.

Task. A task means one or more elements that constitute a distinct activity that is a logical and necessary step in the performance of work by an employee. Tasks are the smallest elements of work job evaluation should address.

Working conditions. The physical surroundings and hazards of a job, such as inside versus outside work, excessive heat or cold, fumes and other factors relating to poor ventilation.

COMMON JOB EVALUATION SYSTEMS

Although scores, and perhaps hundreds, of customized job evaluation systems exist, most can be identified as a derivative of two methodologies: either a *qualitative* or *quantitative approach*. Qualitative methods approach job evaluation on a *whole-job* basis and include the ranking method and the classification method. Quantitative approaches, on the other hand, seek to assign numerical values to job aspects or component parts (factors) with the most common techniques being the factor comparison method and the point–factor method.

Qualitative Methods

Ranking Method. The ranking method can be performed by an individual or a committee and is an acceptable method for small organizations of less than 25. Forced ranking or paired comparison techniques are used to establish the job hierarchy. Following are two examples of this method.

1. *Ranking by job title only.* The title of each job is placed on an index card and the cards are arranged according to relative importance. A wage or salary rate is then established for each job based on whatever data the organization wishes to use.
2. *Ranking by job title and job content.* This ranking method is the same as the previous one, except that the dimension of job content is formally used as an element to judge relative importance.

The ranking method has the advantage of simplicity and the disadvantage of lacking substantiating data for use in justifying the relative position given to jobs. Without standards of comparison, the ranking method becomes arbitrary and tends to maintain the jobs in the same order as before the evaluations.

Classification Method. The second qualitative approach is known by several names: *grading, job classification,* and *predetermined grading.* The classification method is widely used to evaluate administrative and clerical jobs, and is used by the U.S. Civil Service Commission. This method compares jobs on a whole-job basis but improves on the ranking method by introducing factors for comparison. The Civil Service Commission uses the following eight factors:

1. Difficulty and variety of work
2. Degree of supervision received or exercised by the jobholder
3. Judgment
4. Originality
5. Type and purpose of official contacts
6. Responsibility
7. Experience
8. Knowledge

The classification method involves setting up and defining a number of pay grades and then assigning each job to a particular pay grade based on the pay grade definitions. Job evaluation using the classification method requires the following six steps:

1. Establish the system limits by defining the lowest and highest pay grades, then slot the remaining pay grades. Use as many grades as required for the range of jobs being considered. Most classification systems use from 5 to 15 pay grades; the federal GS system has 18; some use up to 30.
2. Define each pay grade using job function information.
3. Describe each job in terms of duties and responsibilities.
4. Match the job description with the most appropriate pay grade description.
5. Determine the job hierarchy and correct any inappropriate job slotting.
6. Assign money values to each pay grade, using available data.

Advantages of this system include its relative simplicity and inexpensive development. The classification system is easily communicated. Prepackaged classification systems with pay grade descriptions are commercially available. Faults with this method include the tendency of evaluators to be influenced by the pay rates, the difficulty of developing grade descriptions especially in larger organizations, and the overall subjective nature of the description preparation process.

Quantitative Methods

Factor Comparison Method. Using the premise that all jobs contain common aspects or universal factors, the factor comparison method represents a more objective approach to job evaluation than the previous methods. The factor comparison method is based on how much more of a specific factor one job possesses over another. The common aspects or universal factors used by this method have become job evaluation standards and include the following:

- Skill
- Mental demands
- Physical demands
- Responsibility
- Working conditions

Other terms used to describe universal factors are *prime factors, compensable factors,* and *job factors.* To minimize confusion, this article will use the term *universal factor.*

The most significant application of universal factors occurred with the Equal Pay Act of 1963. The Act identified four tests to measure "substantially equal work" performed under "similar working conditions." These tests are the universal factors of *skill, effort, responsibility,* and *working conditions.*

Factor comparison improves on the ranking method by comparing jobs in terms of how much of each universal factor the job requires. The use of benchmark jobs is required when using factor comparison. The process starts by ranking each benchmark job, factor by factor, as shown in Fig. 7.2.1. This initial ranking will provide a basis for checking the reasonableness of the system, and it validates the final job hierarchy.

Ranking Jobs by Universal Factors*

Benchmark job title	Skill	Mental demands	Physical demands	Responsibility	Working conditions
Journeyman machinist	1	1	4	1	4
Bench assembler/ tester	2	2	3	2	3
Material handler	3	3	2	3	2
Laborer	4	4	1	4	1

*Highest = 1

FIGURE 7.2.1 Ranking benchmark jobs.

Next, a comparison of the importance of each factor to the total job must be made to understand how much of each factor is required by each job. A simple paired comparison can be performed to determine factor importance within each job. Figure 7.2.2 shows the result of this step.

In the next step, the benchmark jobs are assigned pay rates. Typically, these rates are market rates for similar jobs. These agreed-on job pay rates are then distributed across the factors using

Weighting Benchmark Universal Factors

Benchmark job title	Skill	Mental demands	Physical demands	Respon-sibility	Working conditions	Total
Journeyman machinist	33%	27%	12%	20%	8%	100%
Bench assembler/ tester	26%	24%	28%	14%	8%	100%
Material handler	17%	15%	36%	13%	19%	100%
Laborer	13%	11%	41%	7%	28%	100%

FIGURE 7.2.2 Universal factors by job.

the percentage that has been calculated in the previous step. As an example, the journeyman machinist would have 33 percent of the $18.00-per-hour pay rate credited to the skill factor.

The final step in factor comparison requires slotting all nonbenchmark jobs into the new structure using the same techniques. A completed evaluation is shown in Fig. 7.2.3.

Factor comparison requires a thorough description of each universal factor found in the benchmark jobs. Benchmarks should be common jobs that are easily identified by other organizations and that are uniformly compensated. Several benchmarks are necessary because they will define the group from top to bottom. The proper selection of benchmarks is critical in this job evaluation method.

Benchmark jobs, sometimes called *key jobs,* are selected from three segments of the study group.

1. *Bottom section.* Simple jobs requiring simple skills and limited responsibilities
2. *Midsection.* Jobs requiring a higher level of skills and imposing some responsibility
3. *Top section.* Complex jobs requiring specialized skills and knowledge and higher levels of responsibility

Benchmarks should represent as many departments as possible to provide an overall picture of the variety of jobs within the group and to ensure significant universal factor variation. The

Job title	Skill	Mental demands	Physical demands	Respon-sibility	Working conditions	Pay rate (per hour)
Journeyman machinist	5.94	4.86	2.16	3.60	1.44	$18.00
Quality control inspector	4.50	4.50	2.00	4.00	2.00	$17.00
Bench assembler/ tester	3.90	3.60	4.20	2.10	1.20	$15.00
Assembler A	3.10	3.25	4.00	1.75	1.20	$13.30
Material handler	2.04	1.80	4.32	1.56	2.28	$12.00
Punch tender	2.00	2.00	3.50	1.10	2.00	$10.60
Laborer	1.17	0.99	3.69	0.63	2.52	$9.00
Janitor	1.00	1.00	3.00	0.50	2.00	$6.50

FIGURE 7.2.3 Factor comparison.

duties and current pay rates of these key jobs must be undisputed; if disagreements cannot be resolved, the benchmark job in question should not be used.

Factor comparison improves on the simple job-ranking method by evaluating the universal factors associated with each job rather than solely the whole job. However, several major disadvantages are associated with the use of this system. One of these disadvantages is the extensive evaluator training required. Because market job rates are used in the process, changes will require continuing recalculation. In addition, this system is more difficult to explain to employees, and, if continuous corrections are necessary, it may not be viewed as creditable.

Point-Factor Method

The *point-factor system* (or *point system,* as it is also known) represents the most practical quantitative job evaluation technique. Off-the-shelf or customized point-factor plans are the most prevalent job evaluation systems in use today. Surveys show that the point-factor system is, by far, the most popular approach to evaluate factory, clerical, and professional jobs.

Point-factor systems are based on the notion that all jobs contain varying degrees of the universal factors. In most plans, these universal factors are partitioned into subfactors, and these subfactors are then defined in terms of varying degrees. Figure 7.2.4 shows how a NEMA-type plan, for manual jobs, partitions the universal factors into subfactors.

After partitioning, a narrative descriptor is developed for each degree level of the subfactor as shown in the following example.

Narrative Descriptors

UNIVERSAL FACTOR—SKILL

Subfactor—Education. This subfactor measures the basic education, training, and knowledge required to learn and perform the job to standard. Job knowledge or background may have been acquired either by formal education or by training on lower-level jobs.

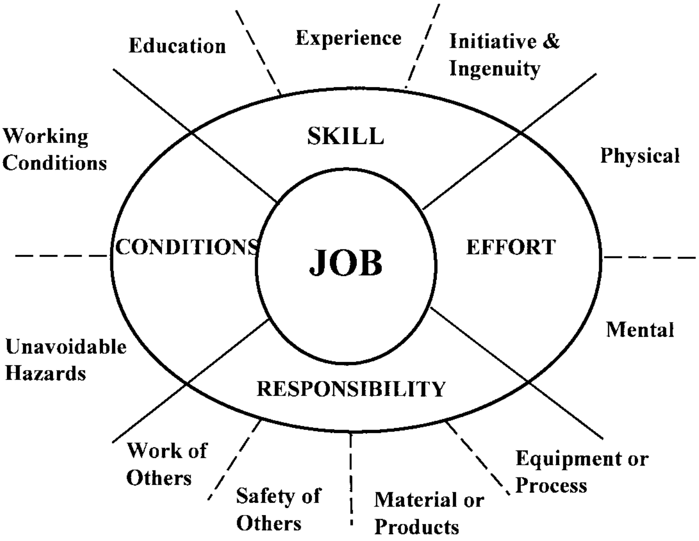
Education
Experience
Initiative & Ingenuity
Working Conditions
SKILL
Physical
CONDITIONS
JOB
EFFORT
Mental
Unavoidable Hazards
RESPONSIBILITY
Work of Others
Safety of Others
Material or Products
Equipment or Process

FIGURE 7.2.4 Universal factors.

- *Degree Level 1.* Requires simple reading and writing, adding, subtracting of whole numbers; carrying out instructions; using fixed gauges and reading simple instruments.
- *Degree Level 2.* Requires using shop mathematics (basic algebra and trigonometry); using complicated drawings, schematics, and specifications. This level is equivalent to completed journeymen craft or trade training, or Associate's Degree–level technical training.
- *Degree Level 3.* Requires using higher mathematics involved in the application of engineering, business, or computer science principles. Comprehensive knowledge of the theories and application of these principles developed through completion of Bachelor's Degree.

During the evaluation process, these descriptors will guide evaluators in the correct application of the plan. Once defined, each degree level is assigned a value, and by totaling the points, the job acquires a point value. All jobs can then be arranged in rank order based on total number of evaluation points.

The point-factor system is focused on internal comparisons of jobs within a homogeneous group. In most cases, definitions of manual factory jobs cannot serve administrative, technical, and managerial jobs, and it is not unusual to find multiple point-factor plans used in larger organizations.

OTHER JOB EVALUATION METHODOLOGIES

This section briefly reviews other job evaluation methods.

Market Pricing

Market pricing uses two basic approaches: (1) pure market pricing and the market pricing guideline method.

Pure market pricing uses links to the external market to establish job worth and is a simple, inexpensive method. Once job descriptions are developed, wage surveys are conducted to determine the *market pay rate* for those jobs. The market pay rate becomes the basis for the internal pay rates. Internal equity is subordinate to external equity in pure market pricing.

The Smyth-Murphy market pricing guideline method improves pure market pricing by permitting internal equity to become a consideration in final job value determination [5]. Smyth-Murphy uses four steps to evaluate jobs

1. Establish a salary guideline scale using a 5 percent difference in midpoints.
2. Prepare realistic job descriptions containing scope data.
3. Conduct the market survey.
4. Develop a horizontal guideline display to ensure internal equity.

Market-based job evaluation methods can be compromised with insufficient or aged survey data. In this respect, wage survey data should be used with caution; differences in job titles, duties, operational descriptions, organization structures, and complexities of equipment or processes vary from company to company. Reliance on survey data based on generic job descriptions may undermine the establishment of an equitable compensation system.

Maturity Curve Method

Organizations use this method to price professional jobs. Wage or income data for specific jobs or professions is collected, and a pay determination is calculated as a function of time since graduation or professional certification. Individual pay is determined by analysis of income trends of the specific profession rather than individual contributions or internal equity considerations.

National Compensation Survey (NCS)

The Bureau of Labor Statistics recently began a project to study the relationship between job duties and earnings. Originally called *COMP2000,* the NCS program calls for the analysis of nationwide earnings data of several hundred occupations. To ensure consistency, a common job evaluation system was developed using standardized point-factor techniques. Ten generic *leveling factors* are used to compare and rank occupations in all industries excluding agriculture, private households, and the federal government.

The new program will combine three independent programs now in use [6]. Nine of the leveling factors found in the NCS program are currently used in the U.S. Office of Personnel Management's Factor Evaluation System. To improve on the System's ability to differentiate between jobs, the 10 leveling factors have been further subdivided into degrees as follows [7]:

1. Knowledge (nine degrees)
2. Supervision received (five degrees)
3. Guidelines (five degrees)
4. Complexity (six degrees)
5. Scope and effect (six degrees)
6. Personal contacts (four degrees)
7. Purpose of contacts (four degrees)
8. Physical demands (three degrees)
9. Work environment (three degrees)
10. Supervisory duties (five degrees)

Hay Guide-Chart Profile Method

Developed by Edward N. Hay in 1938 as an adaptation of factor comparison techniques, this system used three factors to evaluate job content: (1) skill, (2) mental effort, and (3) responsibility. Later, these factors were modified and identified as know-how (KH), problem solving (PS), and accountability (AC). Today, this method, known as the *Hay Plan,* is widely used for the evaluation of executive, managerial, and professional positions. The Hay Guide-Chart Profile Method is also used for the evaluation of clerical, administrative, and factory-level jobs.

Guideline Method of Evaluation

Not to be confused with Hay's Guide-Chart Profile Method, this technique approaches job evaluation from the external market perspective with the usual sequence of evaluation steps reversed. First, a wage survey is conducted to set market rates for key jobs in the organization.

Pay grades are established and the key jobs are assigned to rates based on a matching of the key job market rate to the assigned rate. At this point, the rate assignments are reconciled for internal equity. Nonkey jobs are then slotted into the resulting job hierarchy [8].

EVALUCOMP

This is another external market-focused method. The EVALUCOMP system, developed in 1975 by the Executive Compensation Service of the American Management Association, uses wage survey data to price jobs. Job descriptions are matched, on a whole-job basis, to like positions in the survey establishing a money value for the positions. This system reverses the traditional evaluation process using external market data to establish the job hierarchy.

Time Span of Discretion Technique

This job evaluation technique was developed by Elliott Jaques [9] and does not require a detailed job description. Jaques' method uses only one internal measure, which he found applicable to every job in an organization—the time span of discretion. This is defined as the period of time during which the use of discretion is authorized and expected, without a review of that discretion by a superior. Each job is assigned a time span, ranked, and the job hierarchy created.

INSTALLING A POINT-FACTOR JOB EVALUATION PLAN

A successful installation requires project leadership, employee involvement, technical support, and communications.

Project Leadership

Once the decision has been made to initiate a job evaluation program, it is necessary to decide who will do it. The organization can hire an outside consulting firm to do the entire job on a turnkey basis, choose to do the job internally utilizing qualified company employees, or use a combination of these two approaches. Contracting with an outside firm may be the most expedient way to accomplish the project because they are already trained and experienced professionals, and their work is more likely to be fair and impartial. Third-party impartiality and expertise are important if the results of the project are challenged in a grievance or legal proceeding. The argument for doing the project internally is that company employees will take ownership of the project more readily and come to identify themselves more closely with it because they will be responsible for both its progress and results. Using company employees also provides training for those whose job it will be to acquaint the rest of the workforce with results, and who will be expected to maintain the system after implementation. In many situations, the most productive approach is to use a combination of both internal and external resources.

Employee and Management Involvement

Job evaluation projects should be guided by a central steering committee. Early decisions required of this group include job groups to be included and the type of plan to use. Although it may be desirable to evaluate all jobs in an organization, grouping them together into one plan is seldom desirable. Instead, jobs should be separated into large natural divisions or major groupings.

Once the job group is determined, the type of plan should be selected by the steering committee. Plan selection will depend on the size of the organization, type of business, availability of internal resources, schedule, and implementation costs. Sometimes, the union will want to have a voice in plan selection.

The steering committee will select the job evaluation team. Team members should represent a variety of departments, have a broad range of work experience, and be respected by their peers. Many organizations have successfully used the peer nomination process to select employee team members. Job evaluation teams require permanent members and ad hoc members such as supervisors, industrial engineers, and quality control specialists, for special issues. To ensure accurate data and greater acceptance of the final structure, both direct supervisors and employees should participate as team members. Team members must also play a role in disseminating information about the final job hierarchy and its underlying rationale.

Technical Support from Industrial Engineering

The supporting role of industrial engineering, be it one person or an entire department, in a job evaluation project can take several forms. Industrial engineers may find themselves directing the entire project or serving as analysts during the evaluation process. Often, once the project is completed, industrial engineers become an integral part of the implementation and administration of the company's pay delivery system.

Communications

As part of the initial planning process, a systematic program of employee communications should be devised to keep employees informed of progress through announcements, meetings, and handouts. A successful technique used to increase employees' general level of understanding requires team members to become communication links.

A forum should be established to resolve employee questions before the final evaluation and wage structure is put into place. When the entire project is completed and the overall wage plan is set, employees should be presented with the results in a clear and understandable manner. A written guide to the job evaluation program should be prepared for employee and management reference. Changing an existing plan or installing a new job evaluation plan should be preceded by direct communication to all concerned and should address the following:

- Support from top management
- Support from labor, including a general plan outline and an appeal process
- Pay protection plans for those adversely affected by revaluation of their jobs
- Administration and maintenance of the plan
- Collective bargaining issues in a unionized environment

PLAN CUSTOMIZATION

Plan customization provides management an opportunity to develop a job evaluation system based on unique job relationships and specific job aspects that the organization values. Customized plans can be developed to evaluate all job levels. The following procedures are provided as a guide for those who are interested in a customized point-factor approach.

Choosing the Factors

The universal factors and subfactors ultimately used are determined by a careful study of the scope of jobs to be evaluated. To facilitate factor selection, jobs are grouped into large occupational families (e.g., factory, clerical, supervisory and professional, or managerial). Appendix A contains a list of commonly used factors. Factor selection should continue with the following principles in mind:

- Factors should be pertinent to the type of positions included in the job study. If no supervisory positions are included, there is no point in having the factor *supervision of others.* However, *supervision received* might be appropriate.
- Only significant factors should be selected. It is suggested that 10 to 12 factors be used and that 15 be the maximum number.
- Factors selected should not overlap in meaning. For example, *physical skill* and *dexterity* have practically the same meaning. Select factors that are unique with respect to each other.
- The factors chosen must lend themselves to differentiation in terms of *amount of* the job characteristics that they represent. This means that they must be quantifiable and be described in terms of varying degrees showing a clear hierarchy from bottom to top. For example, *education* can be described in precise terms, such as "8 years of school, high school graduate, or Ph.D. in economics." On the other hand, a factor such as *truthfulness* would be much more difficult to quantify on a scale.
- Factors should not be selected if they will provide all jobs the same rating. This is equivalent to adding a constant to the value of every job and does not contribute to differentiating among the jobs. For example, if all the jobs are performed under the same working conditions, a factor for this job characteristic is not required.
- Factors should represent those job aspects that the organization values and is willing to pay for (i.e., compensable factors).
- Factors selected must be acceptable to both employees and management. If a sufficient number of jobs are extremely repetitive, omission of a *monotony* factor would lead to employee dissatisfaction.
- Reasons for factor selection must be clear and understood by both employees and administrators.
- Factors must be selected with legal considerations in mind. Race, gender, marital status, age, disability, and religion, among other things, may not be taken into consideration.

Factor selection must be based on the work organization, internal processes, the group being evaluated, and management values; this is a complex issue and conflicts can occur. Selecting the correct number of factors to ensure that jobs will be adequately evaluated can minimize conflict. Factor selection of several popular plans can be found in Appendix B. Benchmark jobs aid in factor selection because they can be used to test the applicability of factors and to suggest those that should be included and excluded in the final plan design.

Factor Weighting

Establishing the relative value or weighting of one factor in relation to another is a key design consideration. Weighting reflects the pay philosophy of senior management.

Typically, the skill factors have the highest weight followed by the responsibility factors and the effort and working conditions factors. However, this is not always the case. The CWS plan weights *responsibility* above *skill,* and the NEMA/NMTA-type plans reverse this. CWS emphasizes job responsibility found in processing industries, and the other places emphasis on the job skill and knowledge requirements found in manufacturing jobs. This example emphasizes the importance of matching the plan type, universal factors, subfactors, and weighting to the organization's operations and overall wage administration objectives. Several methods can be used to establish factor weight, ranging from regression analysis to management's opinion. One simple approach used the mathematical procedure called the *normalizing procedure.* Appendix C has an example of the normalizing procedure used to develop factor weights.

Assigning Subfactor Degrees

Plan customization requires assignment and description of degrees or levels for each subfactor. The exact number of subfactor degrees is not standardized, although practice usually limits the maximum to seven or eight. When jobs being evaluated cover a wide range, the number of degrees will be larger than a system covering only a few jobs. Too many subfactor degrees can result in overlapping definitions and confusion, and too few prevent proper job differentiation.

Some designs use an equal number of degrees (NEMA/NMTA-type plan designs use 5 for each subfactor), whereas customized plans can use as few as 3 and as many as 15 to achieve the required job differentiation.

Assigning Points to the Degrees

By assigning numerical values to the subfactor degrees, the measurement scale that will ultimately establish the relative worth of jobs is created.

Once again, a standard is not available and the number of points in a plan can vary. NEMA/NMTA-type plans use 500 points, CWS has only 43, and the Hay Guide-Chart Profile Method uses 6480 points. Because the principle requirement is to provide a basis for job differentiation, the job evaluation method selected and the total number of points used must provide point values that enable the organization to establish an accurate differential between jobs.

Henderson [10] recommends a pragmatic approach to establish the number of points when using one evaluation plan to cover the entire organization. A rough measure of the total points necessary is obtained by dividing the highest salary in the group by the lowest. As an example, if the top annual salary is $200,000 and the lowest $14,560, the plan should have enough points so that the evaluation of the top-rated job would be 200,000/14,560, or 14 times the evaluation of the bottom-rated job.

Applying the Plan

Once a plan has been adopted, job descriptions prepared, the evaluation team selected, employee communications begun, and project leadership assigned, the process of actual job evaluation can begin. The following activities are typical of this process.

Team training. Members of the job evaluation team will require training in job evaluation principles and application of the specific method adopted. A skilled analyst should provide this training.

Documentation. A job evaluation manual must be prepared for the evaluation process, and it is essential that decisions made during the evaluation process be documented in the manual. All job analysis and job description information should also become part of a permanent record.

Application rules and conventions. Application rules and conventions must be created. Several of the most important rules are detailed here.

- Always evaluate jobs on a single factor. Once all jobs have been evaluated on a single factor, the next factor is selected, and the evaluation continues until all factors have been evaluated. It is preferable that each job is evaluated on one factor at a time in order for the evaluation team to develop an appreciation of the full extent of each factor.

- Evaluate benchmark or key jobs first.
- Evaluate only the minimum requirements needed to perform the job in a satisfactory manner.
- All evaluations must be based on the predominant skill and responsibility levels that are regular requirements of the job. In other words, select the factor degree that describes the highest level of skill that is a regular requirement of the job. Typically, all skill subfactors are evaluated using the regular requirement doctrine.
- The *average conditions* doctrine requires that evaluations are to be based on the average degree of effort, concentration, or working conditions associated with the job, not the extremes. The job conditions are evaluated on the average conditions making the job disagreeable. Protective clothing and/or devices required by conditions or state or federal laws mitigate disagreeable conditions and should not be part of the evaluation.
- Jobs are evaluated as if an average trained employee, working at a normal pace, under standard operating conditions, is doing the job. Emergencies are not normally considered in job evaluation unless the function of the job is to respond to emergencies.
- Jobs should not be evaluated based on the volume of work being done, nor should overtime be considered in the job evaluation. It is assumed that jobs are designed to prevent employee fatigue. Overtime is not considered in job evaluation; it is handled outside of the job evaluation plan.
- Rare occurrences and infrequent duties have little or no effect on the true evaluation and should not be listed in the job description nor considered during job evaluation.
- Responsibilities for the actions of a supervisor cannot be credited to a subordinate. For example, a subordinate can call attention to a mistake or problem, but the supervisor need not heed such advice or can determine that the issue is not important at a particular time. Therefore, in job evaluation systems, the supervisor carries the responsibility.
- Benchmark jobs should be considered controlling jobs whenever disputes arise.
- Job descriptions should not be so literally interpreted as to contradict the general sense of an entire factor. The evaluation team should not be influenced by minutiae but should follow the general trend of the factor as it moves upward degree by degree.
- In some plans, responsibility for *safety of self* and/or *safety of others* is a compound factor. The correct evaluation method is to first consider the type of care required to avoid injury, and second, to evaluate the probability of such an injury actually occurring. Often, a review of accident history records is required to determine the true probability of an occurrence.
- An unsafe condition only exists when the protection from hazards must be provided by the actions of the jobholder rather than mechanical devices. In job evaluation, it must be assumed that the required and prescribed safe working procedures, safety apparel, and mechanical safety devices are being used correctly.
- When evaluating a job performed on several shifts, the average conditions should be selected.
- When it becomes necessary to reevaluate jobs due to changes in the job description, only those factors affected by the change should be reevaluated.
- Journeymen and craft jobs are evaluated according to the requirements of the full scope of the craft or trade and the evaluation designated as the standard evaluation for that specific job. Jobs in the apprentice progression below journeyman status are not evaluated by the plan. The apprenticeship pay rate is established on a proration basis.
- Rest time is normally not considered in evaluation of manual jobs. It is assumed that adequate rest time is taken or granted.
- Duration of time must be expressed in unambiguous terms: *occasional* means between 1 and 33 percent of the available work time; *frequent* means between 34 and 66 percent of

JOB EVALUATION

> the available work time; and *continuous* means a duration of 67 percent or more of the available work time. The available work time is calculated by subtracting scheduled breaks and lunch periods from the total clock time. For evaluation purposes, the base unit of time is one shift or workday. Some jobs may require the unit of time to be defined as a week or longer.

After all jobs have been evaluated and a hierarchy established, the task of assigning job grades and job pricing can commence.

Checking the Process

The organization must make every effort to maintain the integrity of the job evaluation process. The simplest method of checking the soundness of the plan is by monitoring employee acceptance, because it is the employees that are most affected by the system and its underlying rationalization. Questions included in employee surveys would allow employees to evaluate and comment on the current system.

Quantitative approaches to check job evaluation systems include using tools that can measure: the effectiveness of each factor, the validity of each factor, and the consistency of plan application.

The effectiveness of each factor is a measure of whether a factor is being fully used throughout its range. A simple tabulation for each factor, listing its degrees and the corresponding number of jobs assigned to each degree will show factor effectiveness. Ideally, one would expect that every factor level be used to some extent.

Factor validity, as it is used here, is a measure of how distinctly one factor is separated from another in the plan. The technique is to determine the level of correlation between the assigned level of one factor with the assigned level of a second factor of that same job. If a high correlation is found between the two factors, there is a possibility that both factors are measuring the same thing and only one may be required.

PLAN ADMINISTRATION AND MAINTENANCE

Job evaluation plans are designed for long-term use. Many plans installed in the 1940s and 1950s are still in use today.

Consistency of application is important to both management and employees. Knowing that the job evaluation system can be relied upon to accurately evaluate jobs year after year is important to the ongoing acceptance of the evaluation system and the wage delivery system in general. In this respect, some unions have negotiated periodic audits of the organization's job evaluation system. One technique used to detect application consistency involves comparing the average rating of each factor at the time of plan implementation with the average factor rating of new or changed jobs evaluated one, two, or more years later. Conducted on a periodic basis, these new average factor ratings when compared with the initial average factor ratings can help prevent evaluation inequities from developing. Differences in average factor ratings will show whether the new evaluations are more generous or more severe than the original evaluations. This technique is also useful to evaluate possible evaluator bias.

THE FUTURE OF JOB EVALUATION

Traditional job-based evaluation programs have come under pressure as organizations change the work structure. Teams have replaced specialists challenging the rationale of job-based pay systems. A substantial increase in the skill-based pay systems to support the new flexible workforce has occurred in recent years.

Job evaluation systems in the future should have flexibility in both factor definition and weighting, and perhaps they will evolve as integrated methods with sensitivity to both jobs and people by evaluating tasks, roles, and competencies.

One new approach is a modification of the factor comparison technique that uses the organization's core values in place of the traditional compensable factors to assess the role of jobs. Thomas B. Wilson, in *Innovative Reward Systems for the Changing Workplace,* describes such a plan developed by Edward Morse of Aubrey Daniels and Associates [11]. In this plan, the organization's job evaluation system is redesigned to analyze the factors that reflect the firm's values, core competencies, and the economic value-added functions. This approach requires new questions to be answered by management at the plan design stage to determine job worth from a customer-focused, value-added framework. Instead of asking traditional questions such as source of supervision, number of employees supervised, and decision-making authority, you ask:

- Who are your customers and what do they need?
- Who are your suppliers and what do you receive from them?
- What value-added activities do you perform to produce what end results?
- What are the key requirements for success?
- What are the primary indicators or measures of your performance?

Questions like these will provide a method to define roles within a customer-focused context and may serve as an important antecedent to new behaviors. Wilson provides a three-step example of the role assessment process, which involves defining the core competencies and key success factors, assessing key jobs by comparing each factor with the role definitions of the jobs, and clustering jobs according to their ranking into job families.

CONCLUSION

Traditional job evaluation continues to be the most reliable technique available to establish a fair, equitable, and competitive pay system. Although the potential for bias in the job evaluation process cannot be ignored, any formal method of job evaluation improves on ad hoc personal judgments made by management in an attempt to rank jobs, and with such a large number of techniques available, any organization can adopt a bona fide job evaluation system that in turn can go a long way toward defending the legitimacy of the organization's pay structure.

With the proliferation of federal and state legislation mandating equal pay for equal work, the outlook bodes well for the continued use of job evaluation techniques. The BLS decision to use a point-factor job evaluation method in the COMP2000/NCS initiative also suggests that job evaluation will be in use well into the twenty-first century.

With this support and no apparent acceptable substitute, we suggest that organizations will continue to rely on job evaluation techniques using the notions of *skill, effort, responsibility,* and *working conditions* to develop the basic structure of their pay systems.

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APPENDIX A Universal Factors and Subfactors

Skill factors (the skill, education, experience required to perform the job)

Education
Trade knowledge
Experience
Accuracy
Initiative
Mental capability
Resourcefulness
Manual skill
Job knowledge
Physical skill
Aptitude
Social skills
Decision-making skills
Leadership skills

Mental development
Schooling
Training
Ingenuity
Judgment
Intelligence
Versatility
Dexterity
Mentality
Details
Difficulty of operation
Complexity
Management skills

Responsibility factors (the responsibility inherent in the job)

Safety
Product
Process
Work of others
Cost of errors
Accuracy
Protection
Plant
Cooperation
Dependability
Coordination
Quality
Records
Contact with others

Materials
Equipment
Machinery
Supervision
Effect on other operations
To prevent spoilage
Physical property
Services
Personality
Adjustability
Details
Cash
Methods
Goodwill

Effort factors (effort expended to perform the job)

Mental effort
Mental or visual
Physical effort
Strain
Comfort
Dexterity

Application of effort
Concentration
Fatigue
Monotony
Routine

Job conditions (those conditions that make the job disagreeable)

Hazards
Danger
Dirtiness
Work conditions
Monotony

Exposure
Surroundings
Environment
Attendance
Travel

APPENDIX B Comparison of Point-Factor Job Evaluation Plans for Manual Jobs

		Work organization or plan type						
		Medium-tech manufacturing	High-tech manufacturing	Process industry custom plan	CWS plan	NEMA NMTA/AAIM	MAYNARD manufacturing	MAYNARD utility industry
Prime Factors								
Subfactors								
Skill		25%	50%	38%	24%	50%	50%	39%
A1	Education/Intelligence						✓	✓
A2	Learning time	✓	✓				✓	✓
A3	Coordination						✓	✓
NEM	Experience	✓	✓			✓		
NEM	Initiative/ingenuity					✓		
CWS	Preemployment training				✓			
CWS	Employment training and experience				✓			
NEM	Education	✓	✓			✓		
TA1	Practical knowledge			✓				
TA2	Manual skill	✓		✓	✓			
TA3	Mental skill		✓	✓	✓			
TA4	Accuracy		✓	✓				
TA5	Dexterity			✓				
Responsibility		35%	30%	20%	52%	20%	20%	44%
B1	Prevent damage materials/product	✓	✓		✓	✓	✓	✓
B2	Direction of others							
B3	Prevent damage equipment/tools		✓		✓		✓	✓
B4	Safety others					✓	✓	✓
TB1	Labor delay			✓				
CWS	Responsibility for operations				✓			
CWS	Responsibility for safety of others	✓	✓		✓			
NEM	Work of others		✓			✓		
NEM	Equipment or process					✓		
BLP	Supervision							✓
BLP	Contacts							✓

Effort		25%	10%	21%	12%	15%	14%	8%
C1	Physical effort	✓	✓	✓	✓	✓	✓	✓
C2	Eye strain						✓	✓
TC1	Mental effort	✓	✓	✓	✓	✓		
HBM	Nervous effort						✓	✓
BLP	Posture							✓
TR	Fatigue			✓				
Work conditions		15%	10%	8%	13%	15%	13%	8%
CWS	Surroundings			✓	✓			
CWS	Hazards		✓	✓	✓			
TR	Working conditions	✓	✓			✓		
NEM	Unavoidable hazards					✓		
D1	Safety hazard						✓	✓
D2	Noise exposure	✓						✓
D3	Suspended-dust exposure	✓					✓	✓
D4	Temperature exposure	✓						✓
D5	Oil/dirt exposure	✓					✓	✓
D6	Water exposure	✓						✓
HBM	Fumes	✓					✓	✓
HBM	Location							✓
Investment							2%	1%
E1	Tool expense						✓	
E2	Excessive clothing expense						✓	✓
Additional factors				13%				
TF2	Job essentiality			✓				
		100%	100%	100%	101%	100%	99%	100%

APPENDIX C Normalizing Procedure

The normalizing procedure is a mathematical procedure that provides a simple approach to weighting a set of universal factors.

Step 1. In this approach, a group of job experts or a job evaluation committee first selects the universal factors and then establishes a rank order for them. (To establish this rank order, the paired-comparison procedure is useful.)

Step 2. The highest ranked factor is assigned a value of 100 percent. Then, a value is assigned to the next highest factor as a percentage of its importance as compared with the highest ranked factor. This relative comparison process is repeated for each remaining factor, always comparing each factor with the highest ranked or 100 percent factor.

Step 3. After all factors have been compared with the highest ranked factor and assigned a value, all the values are totaled. This total becomes the denominator in the determination of the weight of each factor; the numerator is the assigned value. The following example demonstrates the normalizing procedure. This procedure can also be used for weighting the subfactors within each factor.

EXAMPLE *In a customized job evaluation plan, the universal factors were rank-ordered as shown in column 1. Column 2 shows the assigned value as a percentage of the 100 percent factor, and columns 3 and 4 show the division and resulting factor weight, respectively.*

Normalizing Procedure Example

Column 1 (factors in ranked order)	Column 2 (percent of highest factor)	Column 3 (assigned value/total)		Column 4 (weight of each factor)
Skill	100	100/280	=	35.7%
Responsibility	80	80/280	=	28.6%
Effort	50	50/280	=	17.9%
Job conditions	50	50/280	=	17.9%
Total:	280			100.0%

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BIOGRAPHY

Nicholas Davic specializes in wage system design. He has developed and implemented both traditional job-based and skill-based pay systems. As a specialist in the design of group incentives, he has assisted a variety of clients in the design, installation, and administration of variable-pay delivery systems. His experience includes assignments in unionized and nonunion manufacturing, distribution, and service industries in the United States and abroad.

Davic holds a bachelor of science degree in administration and management from La Roche College and has achieved the following certifications: Certified Trainer with Zenger-Miller, Inc., Certified TQM Trainer, Certified in MOST for Windows™ and AutoMOST for Windows™, and Certified Personnel Consultant (CPC).

CHAPTER 7.3

LEAN ORGANIZATION PAY DESIGN

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This chapter describes monetary reward principles that will motivate improved organization performance. Traditional incentive system problems are discussed to provide a foundation and a methodology that can be used to implement a pay system to support lean enterprise principles.

Base compensation must encourage timely product/service delivery to meet customer demand. Pay should reward quality, flexibility, and teamwork because of their importance to everyday operations. Pay should motivate continuous improvement. Management must commit to a pay system that ensures long-term support of lean enterprise principles.

Group rewards may be applied to some organizations in production, processing, distribution, or services, particularly where labor cost is significant. Linking the group reward to a high-level measure provides close alignment of group objectives with organizational goals for output, quality, and cost.

This chapter is based on the experiences of H. B. Maynard and Company, Inc., clients in a wide variety of industries and on the consulting background of the author.

LEAN ENTERPRISE

As the global marketplace matures and customers redefine value, companies find themselves in a fight for survival. Customers are demanding that better products be delivered more quickly at a price comparable to or lower than previously paid. Companies that cannot meet these demands will lose market share and eventually go out of business.

Fortunately, as market pressures mount, a solution is finally being accepted. Lean production had its beginnings at Toyota in the 1940s. Now known by a variety of names, lean concepts are being recognized as being more than a just another program. They are seen as a strategy for survival.

Defining Lean

In simple terms, *lean* means providing your customers with the product or service they desire when they desire it and in the most effective manner possible. The term can be misleading. Since the word *lean* often means living or working with less, some interpret it to mean operating with as few resources as possible. In fact, lean means maximizing the power of your human resources to minimize waste and to better meet customer demand. Lean is a business strategy for growth, not a labor-reduction program.

Maynard has identified eight significant characteristics of a lean organization, as shown in Fig. 7.3.1. These characteristics may be present in any type of organization, whether for profit or not, whether service or manufacturing, whether blue-collar or white-collar.

COMPENSATION

This chapter will focus on the eighth characteristic—*compensation.* Lean compensation systems must support lean enterprise principles. Pay plans should encourage timely product/service delivery to meet customer demand. A plan should recognize quality, flexibility, and teamwork as important to everyday operations. Pay should motivate continuous improvement. Management must be committed to maintaining a pay system that will ensure long-term support of lean enterprise principles.

Base Pay

The primary purpose of base pay is to attract and retain skills and talent needed by a business. Base pay scale is the fixed component of the wage system established by labor market and/or job worth analyses. Base pay should be market-driven, providing employees with competitive pay in exchange for acceptable levels of performance and quality.

Pay equity is both a quantitative and qualitative concept. Traditionally, pay equity is evaluated on two scales, internal and external. Internal pay equity can be determined through various job ranking or job evaluation techniques; in some cases, internal equity is established through negotiation. The ranking assigns job grades, and the external market determines the pay rates to be applied to each grade, as illustrated in Fig. 7.3.2. Employees view one job as "better" than another in a qualitative sense. Quantitatively, the better job must feature base pay that is sufficiently higher than jobs viewed as less valuable to the organization. The pay scale must be constructed with incremental differences between job grades that will motivate people to seek more difficult, more challenging, or maybe even more dangerous jobs than those paying less.

Pay systems are dynamic and must be kept up-to-date. Even a well-designed pay system will develop problems if not properly maintained. A common problem is *wage compression*—

Lean Organization Characteristics

1. Strong **leadership** committed to all lean principles.
2. Effective production and delivery of products and services based on **customer demand.**
3. An exceptionally safe, orderly, and clean **work environment.**
4. A commitment to design and build **quality** into products, services, and supporting processes.
5. A **teamwork** culture where everyone is empowered to make and act upon decisions.
6. Appropriate and active use of **visual management** tools.
7. **Continuous improvement** is an obvious way of life throughout the organization.
8. A **compensation strategy** embracing lean principles.

FIGURE 7.3.1 Lean organization characteristics.

LEAN ORGANIZATION PAY DESIGN

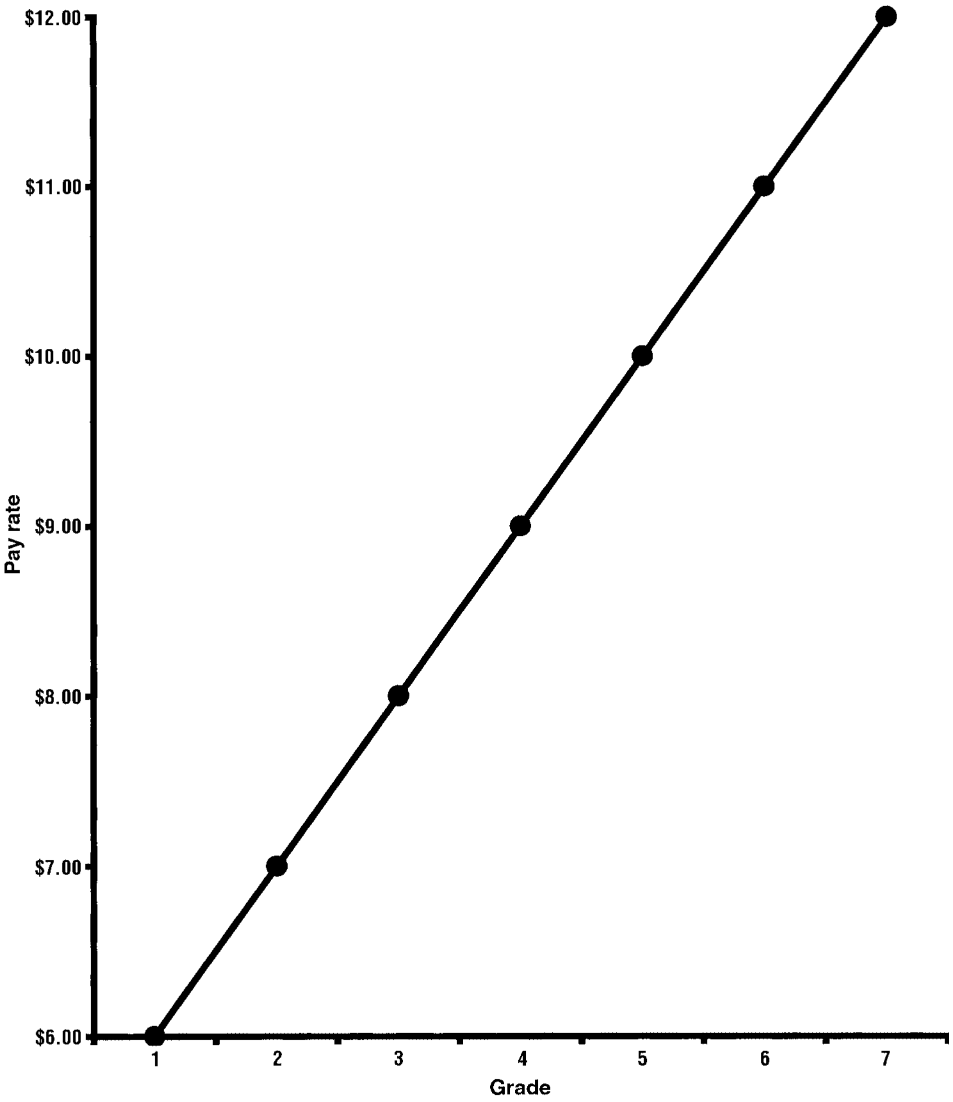

FIGURE 7.3.2 Pay scale.

that is, lack of meaningful difference between the top and bottom of the scale. Compression is due to either a poorly designed scale or the cumulative effects of across-the-board pay increases. As the pay curve flattens, the motivation for employees to climb up the scale is decreased. The traditional pay scale shown in Fig. 7.3.2 is designed with a 100 percent spread between the lowest and highest grades. Across-the-board increases for 10 years will decrease the differential to 50 percent, whereas percentage increases will maintain the 100 percent spread.

Some organizations have tried two-tier pay systems. This usually occurs when an employer has increased wage rates significantly beyond the local labor market. As a cost-cutting measure, the employer decides to place new employees on a lower scale and provides no means for the scales to intersect. Two-tier systems create two classes of employees and always result in friction between the two groups of employees and between employees and management. The author has never seen long-term success with a two-tier pay system, although some companies have achieved dramatic payroll savings with such systems.

External pay equity uses the marketplace to establish job value. Employees are sensitive to the equity issue and expect employers to provide base pay that is fair internally and competitive externally. When employees feel that the base pay system lacks equity, they will look for employment elsewhere. Many recruiting, retention, and motivational problems can be traced to base pay inequities.

Pay systems signal what is valued and what is to be rewarded by the organization—people or jobs. Traditional pay systems value jobs people hold rather than the skills they have and use. Jobs are, in fact, evaluated in terms of the following:

Skill
Effort
Responsibility
Conditions

Capabilities and talents of the individuals holding the jobs are excluded from the evaluation process by design (see Chap. 7.2 for more information on job evaluation). Since job evaluation systems focus on the differences between jobs, they tend to use the difference to justify exclusivity as well as pay level. The effect is compartmentalization of job duties leading to pay squabbles and overtime equalization complaints.

Skill-Based Pay

Pay systems designed for a lean environment should place value on employee skill development and deployment by providing a pay incentive for employees who learn and apply new skills. Employee learning is a major component of the continuous improvement process in a lean environment, and the base pay system is designed to encourage and motivate learning.

The centerpiece of skill-based pay is flexibility to allow the performance of a wider range of tasks and demonstrate a wider range of skills than is possible in a pay system focused only on the duties and responsibilities of a single job. Job families provide career advancement and pay increases proportional to learning time, knowledge, and skill, as shown in the example in Fig. 7.3.3. An employee identifies with a job family (such as product assembly, parts production, or machine operation), each with its own advancement path. A job family supports a manufacturing cell for a specific product. Support teams and maintenance technicians provide services to the product organization and may have separate advancement paths.

Pay tiers provide a range of earning opportunity ($1.00 in the example) rather than a single job rate on the traditional pay scale. A simple job evaluation system will establish the job hierarchy and the basis for pay tiers. Learning is rewarded by pay increments within a tier; cell team members increase their pay by learning additional skills on their present jobs. Promotions offer the opportunity to move to the next tier. Employees prepare for promotion by cross-training to qualify for jobs on a higher tier. The team coordinator is in the line of advancement for positions and occupies the highest wage tier for production jobs.

An organization must establish objective criteria for incremental increases and qualifications for each tier to administer a skill-based pay system. Flexibility charts and cross-training schedules are good tools for tracking employee progress. Apply visual management (Fig. 7.3.1, lean characteristic 6) to prominently display these charts in the workplace. Cell members demonstrate their ability to perform jobs by meeting output defined by engineered time standards, thereby satisfying customer demand (lean characteristic 2).

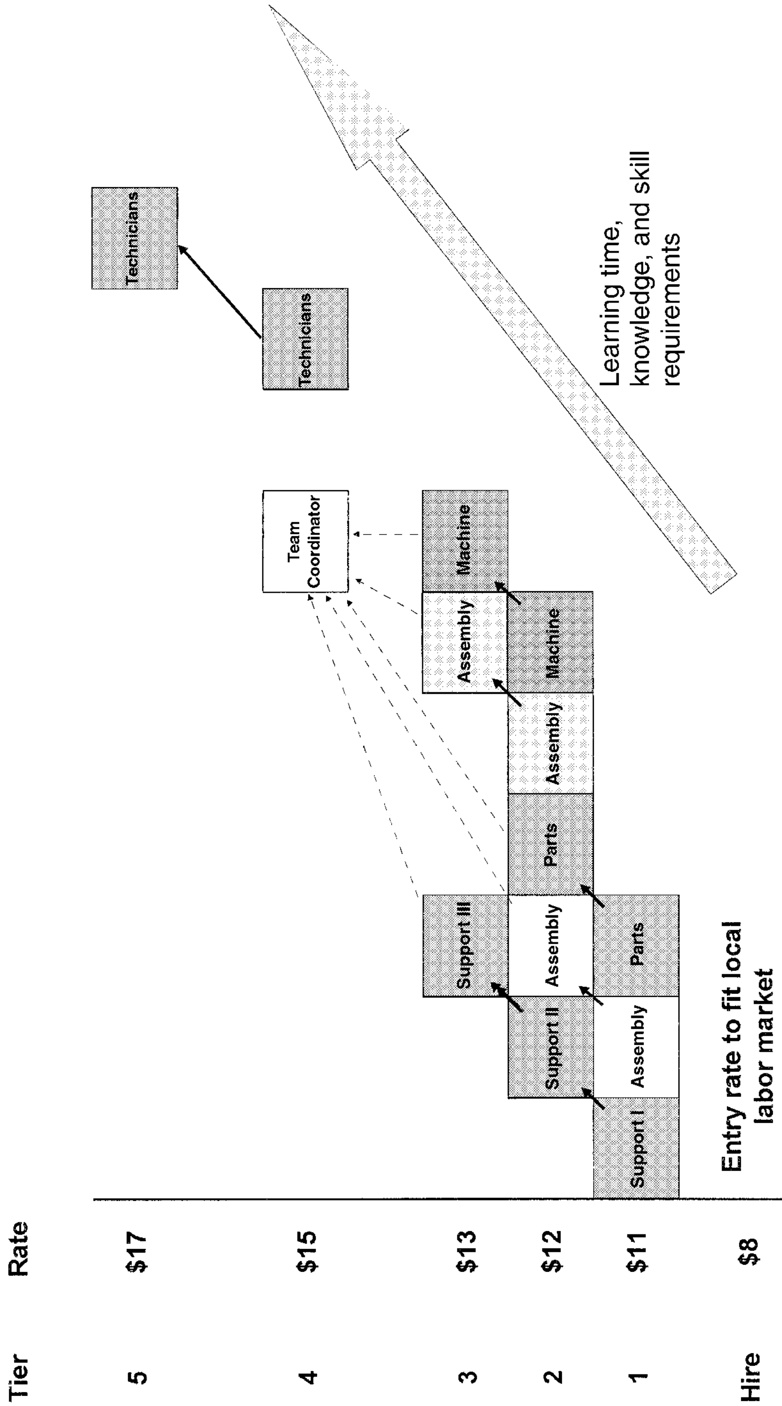
Tier
Rate
5
$17
4
$15
3
$13
2
$12
1
$11
Hire
$8
Entry rate to fit local labor market
Support I
Assembly
Parts
Support II
Assembly
Parts
Assembly
Machine
Support III
Assembly
Machine
Team Coordinator
Technicians
Technicians
Learning time, knowledge, and skill requirements

FIGURE 7.3.3 Skill-based pay model.

Skill-based pay should not be considered a performance motivator. This system rewards employees for skill acquisition; variable pay rewards employees for specific performance results.

VARIABLE PAY

Some lean enterprises choose to recognize employee contributions to organization objectives through recognition programs, awards, and/or a variable pay component. Organization success requires employee commitment, and variable pay based on objective measures can reinforce that commitment. It appears that individual piecework incentives cannot coexist with a truly lean production operation. Traditional production incentive plans emphasize quantity with batch production processes. All too often, output incentive plans are found to be detrimental to quality objectives.

Equitable, market-driven base pay is prerequisite. Variable pay should motivate employee behavior consistent with the eight lean organization characteristics listed in Fig. 7.3.1. That begins with satisfying customer demand for quality products and services (lean characteristics 2 and 4). Variable pay design may reward teamwork, improved quality, and on-time delivery.

Teamwork (lean characteristic 5) is *synergy*—people working together to accomplish more than they could as individuals. Teamwork includes training new team members, helping teammates perform heavy or time-consuming tasks, providing relief to ensure continuous flow, and monitoring quality at each process step. The enterprise benefits are payroll savings (from right-sized work teams), fewer replacement employees, and lower turnover.

Improved quality obviously benefits the lean enterprise and its customers. Quality can be objectively measured by counting defects, with a goal of zero defects. This measure can be translated to variable pay that rewards a team for achieving or approaching defect-free output. Quality bonus may be contingent on satisfaction of customer schedule or team payroll objectives.

On-time delivery is essential to meeting customer demand. Objective work measurement allows the enterprise to plan schedules and staff teams with the resources required to meet customer demand. Satisfying customer demand may be an absolute requirement (or qualifier) for variable pay.

Quantity- or output-driven variable pay is inconsistent with lean organization characteristics. Organizations having an incentive pay culture have a particular challenge in designing and implementing a new pay plan. Incorporation of rewards for meeting lean objectives will help replace variable pay formerly earned with an output-based incentive plan.

Variable pay systems should be tailored to specific enterprise requirements. The author recommends that lean enterprises seek expert pay design assistance.

SELECTING A PAY STRATEGY

Many pay strategies are available to an organization on the "lean journey." The right choice depends on the objectives of the organization and how far it has progressed on the journey. Since pay systems are people systems, organization culture is key to selecting pay strategy.

Some choices are clearly incompatible with the direction an organization is going. The impact of incentive output motivation on customer demand and/or quality requirements rules out piecework as a consideration. Individual economic motivation will overcome the group objectives of meeting (but not exceeding) customer demand. Pay pressure nearly always impacts quality, although the best incentive designs protect quality by paying only for acceptable work.

Alternative pay systems can be compared by using a matrix to see how each system meets the goals of the organization. Figure 7.3.4 shows an example of some criteria that may be used.

Organization Objective	**Job-Based Pay**	**Performance Pay**	**Merit Pay**	**Skill-Based Pay**
Employee attribute focus			■	■
Encourage learning				■
Job/task focus	■			
Seniority/service focus	■			
Results-oriented pay system		■	■	
Objective measurement		■		■
Flexible job assignments				■
Teamwork/problem solving			■	■
Job combinations				■
Bonus payment		■		■
Adapt to technology				■
Increase productivity		■	■	■
Improve quality		■		■
Reduce unit cost		■		■
Reduce seniority emphasis			■	■
Employee advancement			■	■

FIGURE 7.3.4 Pay alternative evaluation.

The matrix compares four alternative pay systems using typical lean organization objectives. Job-based pay values the job and focuses on the task. Seniority and service will be emphasized by job evaluation factors related to learning time.

Performance pay is added to base pay when specific, objectively measured results are achieved. Most incentive/bonus plans provide performance pay justified by increased output, improved quality, and decreased unit cost in a well-designed and properly administered plan.

Merit pay is a way to reflect individual attributes and/or accomplishments in base pay. This individual pay component recognizes individual accomplishment and provides the employee an advancement channel. Merit pay is generally limited to nonunion employees since it is difficult for a union to accept subjective evaluations.

Skill-based pay focuses on the person and rewards individual employee learning. Plan administration requires certified performance to objective standards and posting them for team review. Operating improvement stems from improved productivity, quality, and employee flexibility driving reduced unit cost. Employee satisfaction and career advancement are enhanced by the people focus and by achievement bonuses.

While job-based or skill-based pay can be used to determine base pay, performance pay and/or merit pay may offer a variable pay component. Pay system alternatives may be used in the combination that best satisfies organization objectives.

TRANSITION

Most organizations will need to transition the pay system from where it has been to align it with current organization objectives. Since pay is a people system, it is more difficult to change than a technical process. Change is an essential part of moving from conventional manufacturing practices to lean manufacturing.

Perhaps the best way to describe the transition is to consider experiences of some companies that are on the lean journey. The author consults with organizations that are implementing lean manufacturing, particularly where there are incentive pay implications.

Step One

Ensure that employees do not lose pay by supporting lean initiatives. Incentive employees always protect their paychecks first; other objectives are ultimately subordinated to that one. Many companies handle this issue by paying incentive employees their recent average during the lean project phase.

Guaranteed pay, especially incentive pay for nonincentive work, is contrary to principles of good incentive administration. Make it clear that the guarantee is an interim measure until the lean production process is developed and a new pay system is installed.

Step Two

Select the new compensation approach. If there is an individual incentive plan, it probably will not work in the lean environment. One company intended to replace an individual incentive plan with group bonus and communicated that intent to the employees. During the plan selection phase, management decided that this simple solution was no longer acceptable since a production incentive would compromise the lean objective.

Management appointed a team to work with the pay design consultant to develop a new compensation system. The team included representatives from production, engineering, finance, and human resources who designed a new pay-for-skill system with no performance bonus.

Step Three

Model pay design alternatives to assess impact on employees. In this example, the team modeled alternative incentive and nonincentive approaches for management review. Pay scales were modeled to compare the individual impact of each alternative on every employee in the workforce. The pay modeling approach allowed the client team to consider total payroll cost and positive/negative effects on each employee. All tests were required to meet company objectives without an adverse impact on any individual employee.

Step Four

Select the best alternative. The client team reviewed models and evaluated the pros and cons of each alternative to see how each conformed to corporate culture. A comparison matrix similar to the one shown in Fig. 7.3.4 was developed to focus the evaluation on how well each system met the organization objectives.

LEAN ORGANIZATION PAY DESIGN

The matrix clearly showed that skill-based pay met most company objectives. The cross-functional team was convinced that a performance pay component was required to motivate plant workers since incentive culture was very deep in this company. The team recommended a skill-based pay system with a group incentive umbrella to motivate the workforce.

Step Five

Get management approval. Every pay system needs management approval and support to succeed. In this case, management questioned the incentive umbrella. Top management commitment to lean principles was so strong that the incentive component was considered an unacceptable compromise. The team and consultant reworked the proposed pay plan and increased base rates to match current earnings without the performance incentive. Management was convinced of the merits of skill-based pay and approved implementation in one nonunion plant to validate the design.

Step Six

Test the new design. Select a cell, department, or plant where lean manufacturing is working and test the new plan. Carefully communicate top management's commitment to change and its support for the new pay system. Install the plan and eliminate individual pay guarantees.

In the example, some employees did not have established incentive guarantees and received immediate pay increases. Employees who would lose pay were protected with "red circle" rates for a specified period of time. Management would encourage those employees to acquire new skills to reduce or eliminate the potential pay loss.

The real test of the pay plan is meeting organization goals when people work under the plan. The important goals in a production organization are satisfying customer demand every day with quality goods and services.

Step Seven

Implement the new plan. The pilot area is used to work out any bugs in the plan design. This is normally limited to some minor changes in the administrative side of the plan. More important is establishing a record of success that can be used to communicate the new pay system to the rest of the organization.

CONCLUSION

A compensation system supporting lean principles is required if an organization is committed to becoming lean. Traditional pay systems are job-based, whereas contemporary approaches focus on the individual. Pay for skill is becoming more popular, because learning is rewarded and employee job flexibility helps an organization to achieve its lean objectives.

Changing the pay system is not easy in any organization. Employees will be suspicious about changes, especially if incentive pay is involved. Careful pay design must begin with the base pay structure and be tested for internal and external pay equity. The goal of pay system design should not be to cut employee pay, and two-tier systems are effective only in the short term.

If there is a bargaining unit, changes must be negotiated with the union. The principle of pay equity is very important, and the organization must demonstrate that the goal of the change is not to cut pay. The union must be able to convince its members that a real problem exists and that the proposed pay system will solve that problem.

Team-based approaches are consistent with lean manufacturing principles and should be used to develop new pay systems. Expert facilitation of a pay design team will help ensure that sound pay principles are followed while satisfying organization objectives. Payroll models will help determine individual impacts and overall costs and benefits of alternative pay system designs.

Successfuly implementing a new pay system that supports lean principles will improve employee morale and help an organization achieve its lean objectives of providing customers with quality products and services on time and in the most effective manner. Lean is a strategy for survival.

BIOGRAPHY

David L. Gardner is vice president of H. B. Maynard and Company, Inc., of Pittsburgh, Pennsylvania. He specializes in productivity solutions and has directed a wide variety of client projects to improve methods and processes, quality, productivity, pay systems, and incentive plans. Most recently, Gardner has directed Maynard LeanLine™ Solutions projects. He has experience in manufacturing, distribution, and service industries and has worked with all major international labor unions.

Gardner has over 25 years of industrial management experience with General Motors Corporation, Elliott Turbomachinery Company, and United Technologies Carrier Corporation as a human resource professional and manufacturing manager focusing on productivity improvement. He was director of industrial engineering at Carrier Corporation prior to joining Maynard in 1987.

He graduated from General Motors Institute (now Kettering University) with a B.S. in industrial engineering. Gardner has served as a third-party neutral for the Greater Pittsburgh Labor-Management Committee and has been appointed to the labor panels of the American Arbitration Association and Pennsylvania Bureau of Mediation. He has served as lecturer for the University of Pittsburgh's Graduate School of Business, teaching labor relations and compensation management.

CHAPTER 7.4

REENGINEERING PRODUCTION INCENTIVE PLANS

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Production incentive systems date back more than 100 years and proliferated at the turn of the century. Initially concentrated in the manufacturing sector, they have extended over the years into service and nonmanufacturing enterprises. Properly conceived and maintained, these plans have provided benefits to the companies that implemented them and the employees who worked under them. However, the characteristic history of these plans has too often included the deterioration of the plan due to the lack of commitment to keep the plan measures current. Lack of recognition of this critical requirement has resulted in the deterioration of hundreds of plans and the subsequent loss of benefits to both the companies and their employees. Increasing demands for product proliferation, shorter delivery cycles, and reduced overhead costs created a situation for many companies that made the maintenance of these incentive plans appear less cost-effective than other seemingly more critical projects. Lack of industrial engineering technology to simplify the measurement process and make it cost-effective added to this dilemma. The results were high labor costs and low productivity resulting many times in plant closures and lost jobs.

The 1980s saw the evolution of computerized work measurement techniques and the introduction of processes to reengineer production incentive plans that had deteriorated. This chapter will identify the signs of deterioration for production incentive plans and discuss proven analysis techniques to determine the best process to reengineer incentive plans and, in so doing, revitalize their impact on the company and its employees. Finally, some recommendations will be made for gaining union acceptance for reengineering deteriorated incentive plans and the development of a mutually beneficial solution for both the company and its employees.

WHY INCENTIVES?

Addressing Common Needs

For decades, production incentives have addressed the common needs of employees and employers. Employees want to know what is expected of them. Incentive goals or standards fulfill this need. Employees also feel a greater sense of accomplishment and are highly motivated when financial rewards are provided for exceeding what they perceive to be fair and achievable goals.

From the employer's standpoint, additional productivity lowers unit labor costs, thus allowing them to be more competitive in the marketplace. Higher levels of labor output reduce manufacturing cycle times, which enables companies to better serve the needs of their customers. The incentive pay component of total compensation is variable, depending on performance, thereby providing a no-risk competitive advantage for labor over employers without incentive programs. The use of financial incentives to motivate human performance is actually more prevalent in the salaried ranks than it is in the hourly ranks (sales commission plans, executive bonus plans, and stock options, to name a few). Properly designed and maintained incentive programs for hourly employees can play a major factor in the success of any business enterprise.

Characteristics of Successful Production Incentive Plans

Successful production incentive plans are equitable for the employee as well as the company. They must provide substantial but not necessarily equal benefits for both parties. Incentive pay opportunity must be sufficient to motivate employee behaviors required to reach the targeted levels of productivity. Successful plans support company operating strategies. They increase manufacturing capacity, reduce product costs, and enhance quality. Properly designed plans will encourage teamwork and reward continuous improvement.

Current Trends

Linking reward systems to operating strategies has become the major reason for reevaluating existing incentive plans and designing new ones. The transition from conventional manufacturing processes to lean manufacturing techniques has encouraged movement away from individual-type incentive programs to those that are more team-oriented and focused specifically on achieving company goals. These company goals are most often focused on serving their customers' needs while reducing the cost of working capital, and in so doing, increasing the importance of labor's role in cost reduction.

DETERMINING THE NEED FOR PLAN REENGINEERING

Signs of Trouble

The existence of incentive plan problems is communicated to various parts of the organization, usually focused on human resources and operations. Signs of trouble include stated discontent with the current plan. These communications may come from employees directly to supervision, from union officials to management, or discussions within the management ranks brought on by changing strategies and/or philosophies regarding wage payment and productivity.

Changes in operating strategies, technology, or processes should always trigger an evaluation of their potential impact on the incentive program. Other general signs of problems are slipping levels of quality, increasing production cycle times, increasing product labor costs, and inconsistent administration of the plan between departments or groups of employees.

Since most production incentive plans are standard hour plans based on performance against engineered time standards for units produced, there are a number of areas that specifically relate to and identify potential problems. These areas include employee utilization on productive work that is less than 85 percent of the total shift time, pay performance on the system that is consistently greater than 125 percent of standard, time on incentive which is less than 85 percent of the total hours worked, and finally wide earnings spreads within the same pay grade or base rate. Another critical factor not readily apparent is the lack of industrial engineering maintenance of the incentive plan measures. Processes, equipment, and manual methods characteristically become more efficient over time. Unless these new efficiencies are reflected in revised incentive measures, pay performance rises while productivity or output either stands still or decreases.

Finally, one of the most important but also the hardest area to evaluate is the appropriateness of the base wage structure. High levels of turnover are indicative of situations where the wage structure is not competitive with the area and/or characterized by an extended progression from start to what is considered to be job rate. Incentive pay rates, which are lower than nonincentive rates for the same job, create major inequities in the incentive system, regardless of the accuracy of the measures. In fact, the validity of the incentive measures is often negatively impacted by the need to create higher levels of earnings in order to remain competitive, both internally and externally.

Clearly these warning signs are not always as apparent as they should be and may not be recognized until major negative impacts in labor operations, costs, or the realization that the existing plan will not enforce management's ongoing goals finally lead to the conclusion that the existing plan needs to be reengineered.

Considerations for Reengineering

If one or more of the previously mentioned signs of trouble exist, consideration should be given to an immediate evaluation of the existing incentive situation. This evaluation must start by assessing the existing situation in light of future business directions, the commitment of management to support these directions, the commitment of the union (if one exists) to support change, the potential impact of the cultural change that may be required to restructure the incentive program, and most importantly the potential economic impact of such a restructuring. A number of feasible alternatives must be generated so that a best solution can be established and a practical plan developed to implement this solution.

THE ASSESSMENT PROCESS

The assessment process is key to understanding not only the present situation but also the potential that exists and the factors surrounding this situation that will govern the design of the new plan and the implementation process. The assessment process has two parts: (1) analysis of the current situation including the development of new plan alternatives and the ultimate selection of the new plan, and (2) the detailed implementation program.

The assessment process described in the following section has been developed and used successfully by H. B. Maynard and Company, Inc. for over 20 years. When properly executed, this approach provides all of the data required to evaluate the present situation in regard to feasible alternatives and then quantify the improvement potential of each of these alternatives so that the optimum solution can be selected.

There are nine steps to this assessment:

1. Productivity
2. Wage structure
3. Earnings
4. Measures
5. Plan design

6. Organizational culture
7. Support functions
8. New plan alternatives
9. Improvement potential

A description of each of these steps follows.

Productivity

Productivity is the product of three factors: utilization, performance, and method.

- Utilization is the amount of time spent in productive activity. Typically 85 percent of the total working time is spent in productive activity. Anything less than this can usually be improved.
- Performance is a rating of skill and effort used when working productively. Skill and effort levels vary substantially between incentive and nonincentive situations. A performance of 90 percent is typical of a measured daywork situation where engineered standards are used as measures, but no incentive opportunity exists. Performances from 110 to 140 percent are to be expected in a typical incentive situation.
- Methods level is defined as 100 percent when the workplace methods are judged to meet good industrial engineering practice. Workplace methods are typically found to be between 85 and 100 percent.

The utilization of the participants in the incentive plan would be measured using the industrial technique of work sampling. (For additional information, please refer to Chap. 17.3, on work sampling.) The sampling process is carried out over a period of time to produce a measurement accuracy of ±1 percent of the total utilization number. Both the productive and nonproductive portions of time are divided into subcategories as shown in Fig. 7.4.1. In this example, the components of productive time are manual external, which is time totally controlled by the individual; manual internal, which is time doing manual tasks during a machine or process operation; process time, which is time when no manual work can be done; and setup, which is machine changeover or preparation for another operation. These productive segments add up to 80 percent. The nonproductive time is characterized by delays at 2 percent, idle time at 5 percent, and out of area at 13 percent.

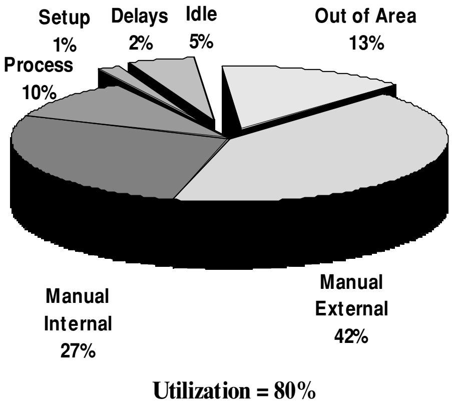


FIGURE 7.4.1 Productivity assessment utilization.

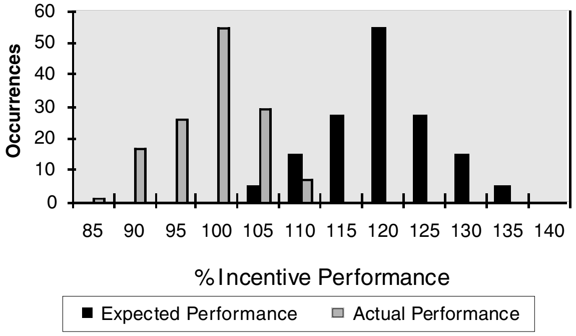
Performance or skill and effort while working productively is measured by trained observers who make a series of random performance evaluations. The result of these evaluations is illustrated in Fig. 7.4.2. In this situation, the distribution of actual performance is shown to the left with an average at 100 percent. The expected performance is shown to the right with an average of 120 percent. The example shows that in this incentive plan, the actual performance is considerably below what would normally be expected.

Finally, workplace methods are reviewed to determine to what extent simple workplace methods improvements can improve this area of productivity. These methods improvements are easily made with no capital expense and are implemented in conjunction with the development of new incentive measures.

The productivity model shown in Fig. 7.4.3 shows that the product of utilization at 80 percent, performance at 100 percent, and a methods evaluation at 95 percent result in a productivity level of 76 percent. When benchmarked against potential for measured daywork (MDW) or nonincentive application, we find that the existing situation is only a percentage point below what we would expect for measured daywork. However, the situation is that this is an incentive, and therefore there is considerable difference between the observed productivity and the potential for this situation.

Wage Structure

Two major incentive plan problems have their root causes in the base wage structure. Base rate structures that provide lower base rates for incentive jobs than their comparable nonincentive jobs, create inequities in the system that ultimately manifest themselves in inflated earnings based on inappropriate measures. These so-called depressed base rates violate the basic rules of a "fair day's pay for a fair day's work" and create undue pressure on those responsible for establishing measures for the incentive plan to create measures that will allow incentive workers to reach a certain level of earnings rather than guarantee a true incentive performance. A related and no less serious problem is the separation of cost of living allowances or other adders from the base rate for incentive purposes. This tends to



Actual Performance 100%
Expected Performance 120%

FIGURE 7.4.2 Productivity assessment performance.

	Observed	Potential MDW	Potential incentive
Utilization	80%	85%	85%
Performance	100%	90%	116%
Method	95%	100%	100%
Productivity	76%	77%	99%

FIGURE 7.4.3 Productivity assessment productivity model.

reduce the incentive base rate even more, and in so doing, reduces the motivational pull of the incentive plan.

In addition to these problems, which relate specifically to the incentive base rates, many base rate structures do not provide competitive entry rates or job rates when compared to the local area labor market. Add to this unnecessarily long progressions from entry to what is considered job rate, and a situation typified by high turnover and poor quality will usually result. The assessment process must include an examination not only of job values but also how jobs are valued in relation to one another and then ultimately to similar jobs in the area. The use of a point job evaluation plan is extremely helpful in this analysis and is especially important when changing manufacturing strategies require different types of jobs or job combinations. (For additional information on point job evaluation plans, refer to Chap. 7.2, Job Evaluation.)

The optimum wage structure is one that has a minimum number of jobs, substantial differences between job grades to encourage advancement, a progression to job rate that is constrained only by the employee's ability to complete a minimum probationary period, and the opportunity for employees to work at a training rate long enough so that they can meet all the requirements of the job description and then can be moved to the job rate when that requirement has been fulfilled. The assessment should clearly determine the shortcomings, if any, of the existing structure and provide recommendations for an improved wage structure that will be consistent with the new plan design and ensure that no inequities (internal or external) are perpetuated in the base wage structure.

Earnings

An analysis of the average straight time hourly earnings of each individual in the plan by job or labor grade will quickly identify the magnitude of imbalances in the pay productivity equation. Figure 7.4.4 illustrates the earnings spreads for the various job grades found in this particular plan analysis. The earning levels of individuals between the lower base-rate line and the upper line indicating 125 percent of base rate are normal. Earnings below the base-rate line indicate progression to job rate. Most importantly, earnings above the 125 percent line indicate out-of-line earnings in terms of true incentive potential. This is a true indicator of loose incentive measures. The earning analysis is also essential to developing corrective actions and combining new measures with new wage structures to design a plan that will be attractive to the employees and solve the inequity problems and the excessive cost created by the existing situation.

Measures

Measures are the heart of the incentive plan design and ultimately determine the earning opportunity of the participants. Typically, physical rather than financial measures are used to determine participant performance and ultimately incentive pay. The most common physical

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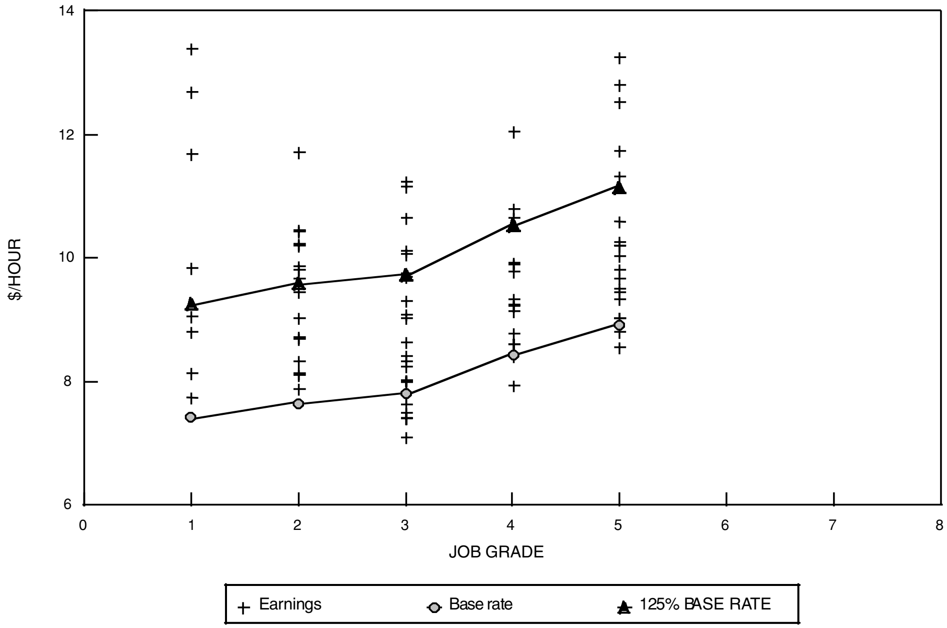

FIGURE 7.4.4 Earning analysis—average straight time hourly earnings versus base rate.

measure is the standard hour that may best be determined through the application of engineered predetermined time systems. This method allows for the accurate measurement of all work required to complete the manufacturing process. The measure is flexible in that it is easily changed as work content changes. Use of a predetermined time system ensures that uniform performance requirements are maintained and eliminates the subjectivity of a performance rating, which is required when stopwatch time study is used as a measurement tool. Application of the predetermined time system using standard data and computerized techniques for establishing process plans and operation standards ensures that with minimal industrial engineering efforts measures can be quickly updated and maintained to reflect current processes at all times. The ability to economically maintain the integrity of the system is crucial to its longevity and to the objective of benefiting both the company and its employees. Failure to maintain incentive measures is the main cause of incentive plan failure. Current industrial engineering work measurement technology makes the maintenance of these incentive measures totally cost-effective. The computerized standard-setting process is used not only by industrial engineers but also by employee teams to determine their own standards for evaluation of continuous improvement projects.

The extent to which the current measures are applied is measured by comparing the hours worked on standard to the total hours worked. This number should be between 90 and 100 percent. Also, allowances for nonproductive activity should be minimized. Proper application techniques can increase time on standard to acceptable levels and also provide for the introduction of indirect personnel as participants in the plan.

Current Incentive Plan Design and Administration

Many times, sound plan designs have been compromised by the addition of exceptions or adders or modified pay arrangements at management's convenience to guarantee a high level of incentive participation. Sound plans provide incentive pay only for incentive performance. Incentives should be regarded as an opportunity—not a guarantee. This philosophy reflects the need to have equitable base wages for all employees and then pay incentive for performance in excess of the fair day's work standard.

Another important consideration in plan design are the provisions of the labor agreement, if one exists. Often contract provisions will be limiting and need to be changed as part of the reengineering of the plan. In all situations, changing incentive plans means changing wage compensation. In a union plant, this is a bargainable situation; in a nonunion plant, it's still "bargainable" to the extent that employee acceptance is necessary to plan success.

Organizational Culture

The feasibility of the recommended plan will be based heavily on the willingness and capability of the organization to make whatever cultural changes are required—for example, moving from a plan based on individual performance to one based on the performance of a group or perhaps the entire plant. The assessment plan uses structured group interviews with approximately 20 employees at a time to develop specific knowledge as to employee feelings about the existing plan, and more important, what they would view as desirable in the design of a new plan. The data developed from these group sessions is invaluable in addressing employee concerns to help gain acceptance of the new plan. A new plan design, which is economically very sound, may not be feasible because of the lack of employee support and acceptance. Careful note must be taken of the real potential for employee attitude changes that will be so important in accepting the recommended plan.

Similar sessions are also held with supervision and management to provide a total assessment of the present company culture and identify the potential impact that the change process may have on the implementation of an improved incentive program.

Support Functions

Typically, incentive participants include only the production workers. However, their ability to be productive is impacted by a number of support organizations that schedule work, provide material, maintain equipment, and monitor quality. And of course, there is engineering, which is responsible for process planning and the establishment of current incentive measures. The assessment process reviews each of these functions carefully to assure that potential levels of productivity identified can be achieved. More important, perhaps, is the assessment of these areas to determine whether they can be included in the new incentive plan design. Also, opportunities for improving these critical services may also be identified as part of the assessment process. One consistent example of this is the improvement of the industrial engineering processes necessary to establish and maintain part process plans and engineered standards.

New Plan Alternatives

The development of new plan alternatives is the result of the analysis of all the previously described steps. Alternatives evaluated will frequently include the ideal solution and then modifications to improve the potential for acceptance. For example, a restructured incentive plan that moves from individual to large group incentives and impacts favorably—at least 80 percent of the employees—will usually be acceptable. A similar alternative that would favorably impact only 50 percent of the employees would have a high level of risk for a higher return. Other factors such as the need to improve the base wage structure to reduce turnover and improve quality would be compared with the investment in additional wage costs. In turn, these costs would be offset by higher levels of productivity made possible through a combination of management initiatives and employee motivation and acceptance. Usually three or four alternatives are developed, and with each, the inherent improvement potential.

Improvement Potential

Real improvement must target company objectives and may often be a combination of labor cost reduction, increased output, quality improvement, reduced manufacturing cycle time, and reduced working capital. The improvement potential is quantified in a way that is acceptable to the company and can be easily explained to the incentive participants. The projection of improvement must illustrate the win-win situation that is crucial to plan acceptance and success. It is not unusual to implement improved plans that share benefits of 30 to 50 percent with the employees. These types of benefits provide the significant leverage needed to continue to be competitive in the rapidly changing world of manufacturing.

NEW PLAN

As the assessment draws to a close, the alternatives are evaluated and the best solution selected. The implementation plan is built around this best alternative. Typically, the new plan will consist of the following steps:

Negotiation
Communication
Employee participation
Training
Measurement
Reporting
Implementation
Monitoring

The scope of each of these steps varies, depending on the implementation requirements. Some general comments about the nature of each of these steps follow.

Negotiation

If a union represents the workers, changes in wage compensation must always be negotiated. Even if the contract allows changes to be made to the incentive plan measures, the extent of change required will normally be so extensive that negotiation will be necessary and desirable. For the new plan to be successful, the union must support it. In this way, the union can be a beneficial force in selling the new plan to the employees. Negotiations may take place at contract expiration, or if changes in the plan are seen to be mutually beneficial, the contract may be opened early with the specific purpose of renegotiating the incentive plan. Appropriate language describing incentive plan provisions is essential to the ongoing success of the plan and should be developed by people experienced in this endeavor. Careful consideration must be given to how the introduction of the new plan will fit into the overall negotiating strategy. In many cases, a new plan can be an asset to the union as well as the company and may be seen by both sides as a bargaining chip. Working with the union to understand the new plan proposal is well supported by the results of the assessment and may be advantageously presented by members of the organization who have conducted the assessment.

Communication

Union or nonunion, employee communication is key to acceptance. Appropriate communications about the results of the assessment and management's decisions should be made in a timely fashion. Employees will be aware that the assessment has been conducted and completed and will be anxious to understand the results since they have participated and provided input into the process. Some limitations are placed on communicating in a union situation since proposals regarding contractual issues must be handled through the appropriate channels.

Employee Participation

In situations where negotiations are not required, employee participation in the finalization of the new incentive plan design is a very practical and positive step. This participation can also be extended to issues relative to job evaluation and the wage structure itself. Finally, during the development of new incentive measures, groups of employees should be involved in technical input for methods and operating practice improvement.

Training

Training, like communication, is an integral part of the implementation process and occurs at different levels of the organization and at different times. Technical training in the use of new work measurement techniques is provided for industrial engineering and union representatives where required. Training in other industrial engineering techniques such as methods improvement, synchronous flow-line design, and kanban development is often also a part of the plan. Supervisory training in performance management is usually provided to augment supervisory skills in managing the productivity of the hourly workforce. In some instances, similar training is provided to hourly team leaders and to self-directed work groups.

Measurement

It would be extremely unusual to find that the measures on which incentive payment is based would not have to be redeveloped to support the new plan. The development of new measures is now able to be done using sophisticated computer software programs that use standard data systems in conjunction with expert logic to provide an automated part processing and operational standard setting system that can establish and change standards in minutes.

Reporting

The days of individual time reporting by operation including a multitude of codes for off-standard situations is being replaced by simplified reporting systems that measure output in finished product on a daily and weekly basis. Whatever reporting is required should be integrated into the information systems used for scheduling and delivery of finished product. Situations still requiring individual reporting can be simplified through a more comprehensive measurement process that eliminates practically all exceptions to routine attendance reporting.

Implementation

Implementation timing, that is, the introduction of the new system to replace the old, is governed for the most part by the new plan design and, in some cases, the labor agreement. Most often, a pilot period precedes implementation for pay to introduce the new plan measures and policies in a manner that will allow correction and modification, where necessary, of supporting systems procedures and perhaps measures. During this time, the new and old systems will be working in parallel. At the completion of the pilot, the old system will be discontinued and the new one will be the only system in use. The impact on information systems needs to be carefully considered since scheduling, costing, and ultimately pay will be impacted by the new system.

Monitoring

Measuring results and monitoring progress toward performance goals is essential to the success of any incentive plan. Key measures to be tracked for the new plan will be developed and tested in the pilot process. Daily, weekly, and trend information for the benefit of the incentive participants needs to be carefully designed and presented in a timely fashion at the beginning of the implementation.

These steps are indicative of the complexity of implementing a new incentive plan and the many facets required to make it successful.

GAINING ACCEPTANCE

Developing acceptance of what will ultimately become the new incentive plan begins at the decision to conduct the assessment. Working with experienced professionals in this field, identification of the need for the assessment and an assessment plan will provide a preview of how the new incentive program may evolve. It is essential that the management decision makers, the union principals (if appropriate), and to a reasonable extent employee groups understand the reason for the assessment process and the probable outcome. With this understanding in place, the assessment process will proceed in a more productive fashion, and conclusions based on study results will be more easily molded into three or four alternatives. These alternatives can then be reduced to one best alternative and an ultimate plan that everyone will be prepared to analyze and eventually accept. The company's acceptance of the best alternative must be backed by an unwavering commitment to the importance of the implementation of the new plan for the ongoing business strategy and success of the company. This commitment perceived by the union and employees will pave the way for more meaningful negotiations and ultimate acceptance of the implementation process. Because reengineering incentive programs are complex, adequate time must be planned for education of union and employees to the needs and benefits of the new program. If the plan is to be negotiated, the education process should begin well before the beginning of normal negotiations so that the plan's acceptance does not become a major stumbling block to normal negotiations.

PLAN IMPLEMENTATION

There are a number of individual steps or projects that make up the total implementation plan. However, overriding all of these are four critical areas of focus. They are commitment, communications, managing results, and maintaining measures.

Commitment

Enough cannot be said about the importance of commitment from management, the union principals, and the employees involved in this process. Part of gaining acceptance of the plan should have been the development of a strong commitment to see the plan through to successful completion. That commitment needs to be constantly demonstrated from the introduction of the program right through to continuous management of the new system. During the program development and implementation, management demonstrates its commitment through its leadership of the steering team responsible for the successful completion of the project. This steering team is made up of key members of the management staff, organizationally structured so that any decision required to ensure the program's successful progress can be made by the team. In a union environment, it is desirable to have a union-management steering team to keep the union officials informed of the program's progress and to deal with any issues that the union may have relative to the program. This team often comprises the union president, vice president, and the union time study representative. Management is normally represented by representatives from human relations, industrial engineering, and operations. The commitment of these groups is manifested in their team charters and is communicated to all employees through a variety of internal media, and more important, visible actions on the factory floor.

Communications

In addition to the steering team, a plan for communicating progress and later results to the employees who will be involved and affected by the program must be an ongoing and active part of the implementation process. Depending on the company management style, periodic employee meetings and small group meetings conducted by appropriate management, possibly with union representation, should be held to inform employees of progress and to field questions as the program moves forward. The company newsletter also provides a good medium for communication. These communications may be augmented by monthly bulletin board postings or a special newsletter designed to track just the progress of the program for the duration of its development and implementation. The key to successful communications is no surprises. As the incentive design process is completed, a brochure describing the new program should be developed and circulated to the employees. A follow-up brochure addressing most-asked questions is appropriate just prior to implementation. Both the brochure and the follow-up piece can be used as the foundation for small group meetings to provide timely answers to questions and prepare the employees and the appropriate management members for whatever changes the new plan may bring.

Managing Results

Typically, problems with the old plan were not identified or quantified until the assessment was conducted. To ensure that there is no repeat of the same scenario in the future, specific operating measures key to managing the new plan will be put in place and monitored on a daily, weekly, and monthly basis. The appropriate measures, of course, depend on the design of the plan. The most common reporting structure for a factorywide incentive program is to monitor cost per standard hour weekly and on a four-week moving average, track plant performance both on a weekly and four-week moving average, and finally, monitor standard hour changes by finished product every six months. If individual reporting is still retained either because it is an individual system or it is used for performance management, individual performance or productivity data should be analyzed based on appropriate employee groups with individual performances rolled up by group and then group to factory. Also, individual average straight time hourly earnings as a percentage of base rate should be tracked on a monthly basis.

Monitoring of these indices by appropriate staff personnel will provide data that is invaluable in managing performance by providing early indications of potential problems. For example, a rising trend in cost per standard hour indicates that productivity is falling or that

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costs are rising disproportionate to productivity. Rising plant performances as well as individual performances and earnings may be indicative of inappropriate or unmaintained measures.

Maintaining Measures

Generally speaking, the effectiveness of any incentive program originates with its measures. Inappropriate measures or measures that are not maintained to reflect current operating situations will quickly create inequities within the plan and skew the plan benefits in favor of the employees. An unwavering commitment to the appropriate resources to maintain measures in the incentive plan is key to its ongoing success. Current industrial engineering technology provides for maintaining operational standards on a daily basis with minimal engineering input. An incentive plan based on properly structured measures should never be allowed to deteriorate because of a lack of maintenance.

CASE EXAMPLES

Individual Incentives

This company employs approximately 500 hourly workers. Two hundred of these workers concentrated in one department work on individual incentives. The need to continually reduce labor costs in a highly competitive industry, coupled with contract negotiations nine months away, prompted the company to reexamine its current incentive plan. An assessment like the one described in this chapter was conducted, and it was concluded that the incentive plan measures were badly out of line with current practices; as a result, earnings were badly out of line with actual productivity. The company used the results of the assessment to work closely with the union officials to come to an agreement to reengineer the plan measures and to modify some contract language to enable the smooth implementation and maintenance of the new system. Upon ratification of the contract, the development of the new measures began, and four months later they were implemented along with the new contract provisions. The communication process during the development of the new measures paralleled what has been previously described in this chapter. A two-week pilot implementation was followed by full implementation, which resulted in almost an immediate increase in productive output with little or no decrease in earning opportunity for the incentive workers. Labor cost reductions in the area of 15 percent have resulted in a more competitive situation that has brought more business to the company while maintaining the same number of employees.

The reengineering of the incentive program resulted in a win-win situation for both the company and the employees. Failure to take these corrective actions surely would have resulted in spiraling costs, loss of business, and ultimately, a loss of jobs.

Product Group Incentive Plan

A series of departmental individual incentive programs were consolidated into a product group plan, including 200 direct and indirect hourly personnel. Participants collaborated with management in the design of the plan and monitored its implementation. Standard hour measures were developed for each product with a weekly bonus being determined by the amount of good finished product produced.

The results after three months of implementation were impressive. Net effectiveness averaged 122 percent: labor cost was reduced 19 percent, overtime was completely eliminated, product yield increased 15 percent, and product cost was reduced 12 percent. Earnings of the participants were equal to or greater than their earnings under the old individual plan.

The process used to develop and implement this new plan was also described previously in the chapter. The absence of a bargaining unit allowed more flexibility for employee involvement and participation. This implementation was the first of a series of implementations that continue today. Each of them focused on different product lines and different geographic locations within the same company.

CONCLUSION

Properly designed and maintained, incentive plans can be key factors in achieving company goals and enhancing a company's ongoing competitiveness. Incentive plans provide opportunities for increased pay for performance, and therefore provide a more competitive wage structure than companies without incentives.

Well-designed incentive plans will continue to provide benefits as long as they are properly maintained. Properly designed and maintained, the cost of ensuring continued benefits from an incentive plan is insignificant when compared with the benefits the plan provides. Continued evaluation and management of results will guarantee success.

In this time of rapidly changing operating strategies to meet increasing customer demands, the importance of employee motivation and dedication at all levels of the organization has never been greater. Incentive systems that appropriately reward the achievement of company objectives in a way that is meaningful to the participants will continue to be the best assurance of success in this rapidly changing environment.

BIOGRAPHY

Roger M. Weiss, president of H. B. Maynard and Company, Inc., is a specialist in the use of employee involvement and reward systems to dramatically improve total company performance. He conducts seminars and executive briefings on the application of the latest management initiatives. He has extensive experience in the area of financial incentive programs and their development, maintenance, and restructuring. He provides specialized direction of client efforts in the development and implementation of production incentive programs. Weiss's 34 years of experience in consulting have included work in process industries, metalworking, fabrication, assembly operations, and service organizations. He is often a participant in wage negotiations with major national unions and has worked with over 400 companies. He is a graduate of Lehigh University, a Certified Management Consultant, and a member of the American Arbitration Association. He has served on the board of the Association of Management Consulting Firms and is a member of IIE.

CHAPTER 7.5

PRESENTING A CASE AT ARBITRATION

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This chapter will discuss what to expect if you ever become involved in an arbitration proceeding. It presents the prearbitration investigation and preparation phases, what to expect at the arbitration hearing itself, and what happens after the arbitration hearing. Many employers whose employees are represented by a union have a grievance and arbitration clause in their collective bargaining agreement. Industrial engineers are often critical witnesses in arbitration proceedings involving disputes over time standards, pay grades, and similar types of disputes. This chapter will be useful to anyone who must present a case at arbitration, and for anyone who must act as a witness in an arbitration proceeding.

PURPOSE OF ARBITRATION

Arbitration is an integral part of any grievance procedure contained in a collective bargaining agreement (CBA). It is the trade-off for a "no strike" clause, and is designed to peacefully resolve disputes over the interpretation of the CBA without a work stoppage or other concerted activity on the part of the union or employees. Binding arbitration pursuant to a CBA is a proceeding in which an impartial judge, selected by the company and the union, makes a binding decision regarding the proper interpretation of the parties' CBA.

Arbitration has many advantages over court litigation—it is a system designed to benefit both the company and the union. Used properly, it saves time and money and preserves the ongoing relationship of the parties. Arbitrators generally are more informed about the workplace than are judges. An arbitrator thus is open to considerations such as the effect of arbitration on shop morale or on uninterrupted production.

Arbitration is designed to be an informal resolution of disputes, but there are different shades of informality. An arbitration hearing often has much of the look, feel, and atmosphere of litigation. The parties sit on opposite sides of the table; the arbitrator is in the middle like a judge; sometimes there is a court reporter; witnesses give sworn testimony; evidence must be introduced properly and be relevant; each side presents its case and must be respectful of the other side and the arbitrator, and so on. Among arbitrators there is a wide variance in degrees of formality, strict reliance on procedural and evidentiary rules, prehearing discovery, and methods of issuing decisions. Typically, an arbitration decision is not only binding with regard to the particular dispute before the arbitrator but also sets a precedent for how the collective bargaining agreement will be interpreted in the future.

Industrial engineers often become involved in arbitration proceedings as witnesses. Examples of the types of disputes in which industrial engineers act as witnesses include disputes over time standards and pay grades. Most CBAs require the arbitrator in such disputes to be an industrial engineer, thus ensuring that the arbitrator will understand the dispute and how the industrial engineers involved arrived at their conclusions.

ARBITRATION IS A PROCESS, *NOT AN EVENT*

Arbitration truly begins with the grievance machinery—generally a multistep process that sets the stage for what happens at arbitration. If either side makes a misstep during the grievance process, this may well affect the arbitration outcome.

PREPARATION: A CRUCIAL STEP IN ARBITRATION

Decision to Arbitrate

If a grievance has not been resolved during the grievance procedure, both parties must make a decision on whether to proceed to arbitration. Arbitration costs time, money, and organizational energy. Every case should be studied carefully before deciding to take the case before an arbitrator. There are several points to consider when making this decision.

1. Alternative remedies: have all other possible solutions been explored?
2. Arbitrability: does the contract contain a clause that allows the moving party the right to arbitrate this particular dispute?
3. Case merits: analyzing this case from the perspective of each party, does it look like a winner? If you cannot win, what is the point?
4. Political considerations: what will be the effect on management and/or bargaining unit members, as well as on the company union relationship? There may be instances where it makes more sense to negotiate an issue rather than arbitrate it.
5. Budget: does the budget allow for the possible expenses that will be incurred? What financial priority should be put on this case?
6. Case priority: is this case more important than others in its immediate and long-term effects on the individual employees and the labor management relationship?

A decision to arbitrate means a commitment to thorough preparation, which actually starts at the beginning of the grievance procedure. The arbitrator's knowledge and understanding is based exclusively on the evidence and argument presented at hearing or in the parties' briefs. Each side must fully understand its own case (and the other side's) to communicate its case effectively to the arbitrator.

Formulate the Issue

If a case is to proceed to arbitration, the first step is the proper formulation of the issue/dispute—what is this case about? It should be put down in words before preparing to arbitrate.

It may change as preparation proceeds, but a framework is necessary to guide the preparation. There are two main questions to ask, and answers must be proven at arbitration: (1) did the action that brought about the grievance actually happen as explained by the grievant, and (2) does this action violate the CBA?

As the advocate prepares the case, he or she must explore and find convincing answers to the following questions:

- What happened?
- Who was involved?
- When and where did it happen?
- Who saw it?
- How is the event covered under the CBA?
- How does this relate to standards generally accepted in the practice of labor management relations and/or to the past practices at the company?

Is the Issue Arbitrable?

Once the issue is formulated, determine whether it is arbitrable under the CBA. Although this question should be addressed before beginning the arbitration preparation process, one should ask it again once the issue is formulated. To determine arbitrability, consider the following:

- Has the union followed procedural requirements?
- Has the union exhausted the grievance procedure and met necessary deadlines?
- Is the substantive issue within the negotiated contractual relationship, that is, does the CBA empower the arbitrator to decide this issue? Remember that an arbitrator can only determine issues involving interpretation or application of the CBA.

Formulate a Theory of the Case

Once an advocate determines that an issue is arbitrable, he or she should formulate a theory of the case. What must the company prove to prevail? What must the union prove to prevail? Who has the burden of proof?

The employer generally has the burden to show it had *just cause* to impose discipline or to discharge. Evidence is used to establish proof of a fact in the mind of the arbitrator. The degree of proof required depends on the nature of the case and must satisfy the arbitrator. There are three degrees of proof used by arbitrators in making decisions:

1. *Beyond a reasonable doubt*—this is used only rarely, because it is a criminal law concept.
2. *Clear and convincing*—this is used in the majority of cases.
3. *Preponderance of the evidence*—the minimum degree of proof necessary.

The following principles should guide the advocate in formulating a theory of the case and presenting the case at arbitration. Did the employer's decision contain one or more elements of arbitrary, capricious, unreasonable, and/or discriminatory action? Did the employer give the employee adequate forewarning of possible disciplinary consequences of the employee's conduct? (This can be oral or in writing.) Was there adequate compliance with the step process—did the employee receive proper prior counseling and warnings? If the employee has a prior relevant record of similar misconduct or poor performance, was this noted on prior steps? (Keep in mind that some offenses are so serious that the employee should know the conduct is prohibited even if not so informed by the employer.) Was the rule/order reasonably related to the orderly, efficient, and safe operation of the business? (An employee may justifiably disobey an order or rule if he or she sincerely feels obedience would seriously and immediately jeopardize personal safety or integrity.) Was the company's investigation proper (including due process considerations)? Was a union representative present during interview of grievant? Did the employer make an adequate and objective effort to determine whether the employee disobeyed a rule or order? Was the employee given a chance to tell his or her story? Was the employee given the chance to confront accusers? Did the employer's investigation obtain substantial evidence of the offense? Has the employer applied its rules, orders, and penalties in an evenhanded manner?* Was the penalty fair, based on the seriousness of the offense, the employee's length of service, and previous offenses. If the penalty is not fair, what is? The union will try to show mitigating circumstances and lessen the penalty.

In a case of contract interpretation (which may also be part of a discipline/discharge case), keep in mind that in determining the meaning of a particular collective bargaining agreement provision, the arbitrator's primary concern is to administer the intent of the parties as spelled out in the agreement. The language of the agreement is at the core of the determination. An arbitrator will enforce clear and unambiguous language even if the outcome does not appear equitable. Specific language is given more consideration than general, and specific exceptions to the general rules should prevail. Arbitrators typically hold that to express one thing is to exclude another, and that words are judged in their context. Moreover, most arbitrators agree that the agreement must be construed as a whole so that a certain interpretation of a provision should be consistent with other provisions and should not render another provision superfluous or meaningless. The primary rule is to read words and sections as part of the total agreement. Words should be given their ordinary and technical meaning unless it is shown that both parties intended otherwise.

Arbitrators typically consider certain evidence beyond the contract to determine the intent of the parties. Such evidence may include the history of negotiations as evidenced by minutes or records. Such evidence also may include what is called *custom and past practice,* which is a "uniform response to a *recurring* situation over a *substantial* period of time when that response is known or should be known by *responsible* union and company representatives." In other words, how have the parties implemented the terms of the collective bargaining agreement? When the agreement is ambiguous or silent on a particular issue, past practice is particularly critical.

Many arbitrators also recognize the *reserved rights doctrine,* which provides that management reserves all necessary rights to manage the plant and direct the workforce, absent clear contrary language in the CBA. Some arbitrators view the doctrine more broadly than others.

Thorough Fact Investigation

A thorough investigation of the facts should already be completed during the grievance process. Such an investigation includes a detailed chronology of events, an interview, and an evaluation of potential witnesses (including potential adverse witnesses, i.e., hourly employees who "know something"), identifying and gathering potentially relevant documents and determining what facts and documents are missing.

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* The union typically will allege disparate treatment, that is, that the company has imposed a harsher treatment on the grievant than on others. But remember: to prove disparate treatment, it is not enough for the union to prove that one or two other employees received lighter penalties. The union must demonstrate that the lighter penalties were for the same or similar offense under the same or similar circumstances with the same or similar mitigating factors.

When selecting witnesses to testify, remember that *more is not always better.* Use quality witnesses who appear credible, know the facts well, are good communicators, and can hold up under aggressive cross-examination. If you do not have to use a witness to establish a fact, do not.

Relevant documents can include grievance papers, discipline/discharge papers, comparables or other documents that show past practice, relevant practice agreement language, other paperwork regarding disputed company action (statements, meeting notes, etc.), and relevant bargaining history as reflected in notes and minutes. Study every potentially relevant document as part of a thorough investigation.

Witness Preparation

One of the most important aspects of preparing for an arbitration hearing is preparing witnesses to testify. Many arbitrations go awry when a witness says what he thinks his side wants to hear, or tries to rehabilitate himself when he believes his testimony is going badly.

Witness preparation must include the preparation of witness outlines for both direct and cross-examination. Nevertheless, an advocate must not be afraid to deviate from an outline. Often the best examinations are those that "roll with the blows."

In preparing witnesses to testify, determine the weak points of your case and how to address them in a credible manner. Sometimes witnesses have to admit bad facts to preserve their credibility. Conducting a practice cross-examination with the witness is often more important than practicing the direct testimony. The witness must be prepared for hostile questioning on the stand.

The purpose of preparing witnesses is not to tell them what to say, but rather to help them to be comfortable with the facts and with testifying. But remember, overpreparation can result in witnesses appearing coached, which can damage their credibility. Nervousness on the witness stand is to be expected and can even bolster credibility.

Finally, the problem of missing witnesses (unwilling to testify, quit, fired, deceased) cannot be ignored. If a party can establish evidence showing an effort to obtain a missing witness, then an arbitrator *may* admit hearsay evidence, providing it is reliable.

Prearbitration Discovery

Typically there is no formal prearbitration discovery, because facts and documents have been informally exchanged during the grievance process. Nevertheless, both parties have the right to request documents relevant to the grievance, as well as the obligation under the National Labor Relations Act to provide such documents on request.

The arbitrator technically is without power to compel production of documents (except possibly in specific, limited circumstances). If one side refuses to provide requested relevant information, however, the requesting party can file an unfair labor practice charge at the National Labor Relations Board. Moreover, the arbitrator may consider the fact of nonproduction in deciding the case.

Prepare Exhibits

An advocate should have three copies of each exhibit, one for the arbitrator, one for the other side, and one to keep. Exhibits at arbitration will either be documentary or demonstrative. Demonstrative exhibits may include diagrams, photographs, pictures, and things. The goal is to most effectively (and efficiently) communicate facts to the arbitrator. As always, a picture can be worth a thousand words. Cases often turn on very fact-specific issues, which can be best illustrated with photographs or diagrams. However, only use well-prepared, well-thought-out diagrams or charts. Otherwise, they may be confusing and detract from the presentation of the case.

ARBITRATION PRESENTATION

Location and Physical Layout

Parties usually have a specific place where they hold arbitration hearings, often a meeting room in a hotel near the plant. A typical layout of the room for arbitration hearings is a U-shaped table. The parties sit around the outside of the U, one on each side. The arbitrator sits in the middle. The advocate for both sides sits closest to the arbitrator. Witnesses typically sit next to the arbitrator, or near the center of the U. Often there is a court reporter who records the hearing verbatim.

The advocates typically give their opening statements and examine witnesses from their seats, standing up only if necessary to hand exhibits to a witness or use demonstrative exhibits.

How to Dress

Dress codes will depend on the practice of the parties. Company managers typically wear suits and ties. Supervisors and hourly employees often wear their work uniforms, if applicable.

How to Conduct Yourself

It is important to treat the arbitrator and witnesses with deference at all times. Although arbitration is less formal than court proceedings, the arbitrator should be treated as one would treat a judge in a courtroom. To maintain order, issues or difficulties with the other party should be addressed to the arbitrator, not to the other side.

Order of Proceedings

Stipulation of Facts/Issues. Prior to the hearing, the parties should meet to discuss the issue(s) they want the arbitrator to decide. They also should discuss whether there are any undisputed facts to which they can stipulate. Finally, they should determine whether there are any exhibits that can be presented to the arbitrator as joint exhibits. At the very least, the relevant CBA, the grievance, and the company's answer typically are presented as joint exhibits.

Depending on the practice of the parties, they often will also exchange witness lists and exhibits at this meeting. The timing of the meeting will depend on the parties' practice. A meeting held one or two days prior to the hearing is more helpful than one held on the hearing date.

The parties may or may not be able to stipulate to facts or issues. It is a good idea to try to do so, however, because such stipulations save time at hearing by limiting necessary witnesses. The same is true for joint exhibits. A joint exhibit does not require a witness to authenticate and explain it for it to be admitted into evidence.

At the very start of the hearing, the parties should present joint exhibits, stipulations of fact, and the stipulated issue to the arbitrator. If the parties are unable to stipulate to an issue, the arbitrator generally will ask each party to offer its statement of the issue and explain why its statement is appropriate. Some arbitrators will ask that this be done prior to opening statements. Others will ask the parties to incorporate it into their opening statements.

PRESENTING A CASE AT ARBITRATION

Opening Statements. Each side then is given the opportunity to make an opening statement to the arbitrator. The opening statement is very important because it is the arbitrator's first exposure to the case. You should briefly state your position, present primary relevant facts, and give a concise statement of why your position should prevail in light of the facts. The advocate should focus on the facts rather than argument. Do not provide a litany of unconnected facts: try to tell a story. Paint a picture of the atmosphere of hostility at the plant, or the myriad ways in which the company tried to work with the union to resolve a disputed contract issue to no avail. Consider introducing any bad fact in your opening statement so that you can put it in the light most favorable to you from the start.

Generally, the party with the burden of proof gives its opening statement first. The other party can give its opening statement immediately thereafter, or wait until the first party has presented its case. In most cases, it is beneficial to give the opening statement immediately so that as the arbitrator hears the other side's evidence, he or she will be able to evaluate it with your position in mind. Otherwise, the party who proceeds first tells the arbitrator its entire story, including presenting all of its evidence, before the arbitrator hears anything from the other side.

Order of Proof. There is no absolute rule on which side proceeds first, absent provision in the CBA. In general, however, the party with the burden of proof proceeds first. Thus, the company proceeds first in cases involving discipline or discharge, and the union proceeds first in other cases.

The side that proceeds first also is allowed to present rebuttal evidence after the other side presents its case. The other side then can present evidence to rebut the rebuttal, and so on. Generally rebuttal is limited to responding to evidence the other side just presented.

Order of Witnesses. The advocate should have a coherent strategy regarding choice, order, and examination of witnesses. Normally (and especially in discipline/discharge cases) the bulk of the evidence is going to come in through witness testimony. It is thus important to map out what you want to accomplish with your witnesses and how best to accomplish those objectives. Remember, quality is more important than quantity. Put as few witnesses on as possible to establish your facts, since you cannot guarantee what a witness will say or how he or she will survive cross-examination.

Order the witnesses such that foundation for one witness's testimony is laid before he or she testifies. Proceeding backwards may well confuse the arbitrator, and almost certainly will diminish the impact of the testimony. You want the arbitrator to be listening to the direct testimony, not trying to figure out how the evidence is relevant to the case.

Consider putting on first the witness who has the most complete story to tell. Chronological order is another way to proceed. On the other hand, you may want to start strong and finish strong. *Do not* start or end with a weak or vulnerable witness, if possible. Try to follow up a relatively weak witness with a strong witness.*

Examining Witnesses. The advocate examines witnesses in two ways: direct and cross-examination. Hostile or adverse witnesses will be cross-examined, while favorable witnesses will be placed on the stand on direct examination. The party presenting the witness proceeds first with direct examination, and the other party then has an opportunity to cross-examine. The first party then may redirect, the other may recross, and so on until both sides have finished with the witness. In certain circumstances, a party may call a witness as a hostile or adverse witness, in which case the cross-examination of the witness will proceed first.

Direct and cross-examination involve very different strategies, and different forms of questioning. On direct examination, the witness generally should do most of the talking. On cross-examination, the examiner should do most of the talking.

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* Obviously, some of these general rules may conflict with each other in a given case. Therefore, they are guidelines only, and each case requires that the advocate balance the competing concerns.

Direct Examination. You must outline the facts that you need to establish through each witness and structure your line of questions accordingly.

Background. First establish who the witness is, and how he or she fits into the story that you are telling the arbitrator. Before the witness gives substantive testimony, it is necessary to lay a foundation explaining how the witness knows what he or she will claim to know.

Form of Questions. The form of the questions will depend on how articulate the witnesses are and to what they will testify. If you have confident, articulate witnesses, you should ask open-ended questions and let them tell the story with minimal interruption. Less confident witnesses will require more prompting.

Foundation. Before a witness is permitted to testify, you must show that the evidence is relevant, that is, you must show that the evidence relates to some issue that is important to the case at hand. You further must show that the witness is qualified to provide the testimony (i.e., how does the witness know?). If this was not made clear in the witness's answer to background questions, then it has to be further explored before the witness can testify about a specific event.

In a dispute over engineered rates, one witness likely will be the industrial engineer who established the rates. A proper foundation will be laid for that witness by simply establishing that the individual is an industrial engineer and that he or she established the disputed rates.

Similarly, a likely witness in a discipline case is the employee's supervisor. A proper foundation will be laid if it is established that the witness supervised the employee in question, during the time period in question, and was involved in issuing the discipline to the employee.

Another aspect of laying a proper foundation is that there must be testimony that an event occurred before a witness can testify about the ramifications of that event.

Maintaining Witness Credibility. Witness credibility is essential. Arbitrators often consider these factors to determine credibility: (1) the witness's demeanor while testifying; (2) the character of the testimony; (3) the witness's capacity to perceive, remember, or communicate; (4) the witness's character for honesty; (5) the existence of bias, interest, or other motive; (6) prior statements made by the witness that are either consistent or inconsistent with the testimony; (7) the witness's attitude toward the grievant's complaint; and (8) any admissions of untruthfulness by the witness.

The examiner should give the witness advice on maintaining credibility during witness preparation. That advice should include the following: (1) tell the truth, (2) do not be defensive, (3) do not look to the examiner for answers, and (4) be confident, not cocky. Credibility is damaged when a witness is unwilling to admit a mistake or bad facts. For example, a supervisor must be willing to admit—without defensiveness—that he or she lost his or her temper in administering discipline. It often is effective to bring out the bad facts on direct examination, so as to cast them in the best light.

The Nervous or Forgetful Witness. It is natural for witnesses to be nervous, particularly if they have never testified at a hearing. If the witness is excessively nervous, however, the examiner should consider asking the arbitrator for leave to ask leading questions until the witness becomes more comfortable. Sometimes witnesses forget, even if they just told you facts in preparation yesterday. The examiner can refresh recollection by showing a document to the witness, such as minutes from a meeting. If the witness has forgotten a major point, the examiner must get the witness to say it, even if the examiner has to resort to leading questions. If it is a minor point, however, the examiner should consider dropping it so as not to damage the witness's credibility.

Introducing Documentary Evidence Through Witnesses. If the parties do not agree to make a document a joint exhibit, then it must be introduced into evidence through a witness.

The examiner should first mark the document as either a company or union exhibit, and give it a number, for example, Company Exhibit 1 or Union Exhibit 1. The exhibits introduced by either party should be numbered sequentially.

AUTHENTICATION: After the exhibit is marked, it must be authenticated by the witness. The witness must testify that it is what it appears to be. The witness further must identify its origin, either because the witness has seen it, signed it, recognizes the signature, or knows it to be a document kept in the ordinary course of business (e.g., a disciplinary step note—issued to employees receiving discipline and kept in their personnel file).

The testifying witness must have created, reviewed, signed, or received the document from the other party. Alternatively, the witness must be able to identify it as a record maintained in the ordinary course of business. In that instance, the witness must either use the record regularly in carrying out his or her job duties, or must be the custodian of the particular record.

The following are examples. Any of these witnesses could authenticate a disciplinary notice: the supervisor who issued it, the manager who approved its issuance, the personnel manager who maintains the personnel files in which disciplinary notices are kept, the employee to whom it was issued, or the union representative who received a copy of it from the company. Similarly, a production record could be authenticated by the individual who created it, a supervisor, manager, or industrial engineer who regularly used it to track production, or a production clerk who maintained the files in which it was kept.

RELEVANCE: Both documentary evidence and testimony must be relevant, meaning they must have some bearing on an issue in the case and are not merely inflammatory.

MOVING INTO EVIDENCE: The next step is that the examiner should ask the arbitrator to admit the exhibit into evidence. If there is no objection, the arbitrator will receive it in evidence without formally "moving" it into evidence. The examiner should ask what the arbitrator's practice is in this regard, however, so that critical evidence is not lost on a technicality.

RESPONDING TO OBJECTIONS TO TESTIMONY/DOCUMENTS: The other side may object to your witness's testimony, your questions, or your documents. The arbitrator may rule independently, but most will ask for your position before ruling. You should explain why you think he or she should consider the evidence. Focus on its relevance to the case, and respond to the other side's specific objections.

Cross-Examination

Purpose. There are several goals associated with cross-examination. The first goal is attacking the witness's credibility or impeaching the witness. The witness's story may be a recent fabrication, in which case you may be able to impeach the witness with prior inconsistent oral or written statements. You also may be able to establish contradictions among the testimony of different witnesses, or establish a bias, prejudice, or motive to lie (i.e., the witness's relationship with one party or with grievant, bias against supervisor involved, or incentive not to self-incriminate).

The cross-examiner also should attempt to attack the witness's competency, recall, and retention. If the witness was not in a position to know or observe what the witness claims, that should be brought out on cross-examination. In addition, the witness's inability to recall other things about an incident can cast doubt on the witness's ability to remember what he or she claims to remember.

A second goal of cross-examination is to elicit helpful information. An effective cross-examination should highlight important things that were left out of witness's direct testimony.

Determining When to Cross-Examine. Cross-examination is not always useful, and should not be used in every instance. If the witness's direct testimony was so vague as to be useless, the examiner may not want to cross-examine because it would only clarify that testimony. Similarly, if the witness has been truthful and accurate, cross-examination may simply reinforce the testimony.

Rules of Cross-Examination. Cross-examination is very different from direct examination. The examiner should ask leading questions, limiting the witness as much as possible to "yes" or "no" answers. The examiner should not have the witness repeat harmful testimony, because that simply allows the arbitrator to hear it a second time. An examiner should try not to ask questions unless he or she is reasonably certain of the answer. "Fishing expeditions" should be avoided because they often result in further harmful testimony.

In an effective cross-examination, every question should have a purpose. You should be leading the witness to a serious contradiction, casting doubt on his or her knowledge of the facts, or demonstrating his or her unfamiliarity with important details. Do not ask the witness to explain testimony. One of the most important rules of cross-examination is to *know when to stop!* If you allow the witness to explain, the damage done to the witness by an otherwise effective cross-examination may be undone.

When impeaching the witness, first have him or her commit to his or her testimony before pointing out a prior inconsistency. Do not first show the witness the document that demonstrates the inconsistency, or the witness can waffle.

Finally, there is a fine line between destroying a witness's credibility and casting the witness in a sympathetic light. If an examiner attacks a witness too harshly, the arbitrator may begin to sympathize with the witness. Further, remember that in the labor setting all of the parties—and witnesses—typically have to continue working together. Consider the impact of an overly rigorous examination.

Evidentiary Matters

Most arbitrators do not follow legal evidentiary rules strictly, especially when nonlawyers are presenting the cases. All relevant evidence usually is admitted despite technical evidentiary shortcomings. Nevertheless, some evidentiary rules are enforced by certain arbitrators. Moreover, most arbitrators will give less weight to legally "deficient" evidence, such as hearsay. A presenter should be prepared to object to certain types of evidence so as to call the arbitrator's attention to its deficiencies, even if the arbitrator ultimately accepts it into evidence. Therefore, it is important to understand some basic evidentiary rules.

Relevance. Evidence is relevant only if important to an issue involved in the case. Although arbitrators will let most evidence in "for what it's worth," a presenter should be prepared to discuss the irrelevance of evidence introduced by the other side. Such irrelevance should be pointed out by way of objection, in closing arguments, or posthearing briefs.

Hearsay. Hearsay is a very complicated and often misapplied rule of evidence. Because hearsay evidence will be given less weight by an arbitrator, it is important to know a few basics.

Hearsay is an out-of-court (out-of-arbitration hearing) statement by someone other than the witness offered to prove the truth of the matter asserted in the statement. An example of hearsay is a statement by an hourly employee witness that "Joe (another hourly employee) told me that he saw Bud run his forklift into a wall," offered to prove that Bud ran his forklift into a wall.

The problem with a hearsay statement of this type is twofold. First, the witness has no personal knowledge of the alleged event so he or she cannot vouch for the truthfulness of the statement. Second, speaker Joe is not available to be cross-examined and observed for credibility purposes. Therefore, it is impossible to determine whether Joe was telling the truth when he made the statement.

A discussion of each element of the definition of hearsay may make it easier to understand.

An *out-of-court* statement simply means that the statement was not made in the arbitration hearing. It may be either an oral or a written statement.

Offered for the truth of the matter asserted means that the out-of-court statement is offered to prove that what the statement says is true. If it is offered for something other than the truth of the matter asserted, it is not hearsay. For example, a manager who testifies that employee A told him or her employee B had stolen tools in his or her box with the purpose of showing that Employee B stole the tools is testifying to hearsay. If the purpose is to show why the manager searched employee B's toolbox, however, the testimony is not hearsay. A statement is not hearsay if it is offered merely to show that words were uttered (for instance, to show a slanderous statement). It also is not hearsay if offered to show the state of mind of the person who made the statement.

An admission by the opposing party is not hearsay. That means that the union can offer statements made by company representatives, and vice versa. Such statements are not hearsay.

Even if a statement is hearsay, there are certain exceptions that allow the evidence to be admitted and considered. Testimony taken at a former hearing/arbitration is generally admissible, even though it is hearsay. A declaration by a person against that person's interest is generally admissible. An excited utterance made as part of the happening of the event is admissible. Finally, one of the most important exceptions to the rule against hearsay that arises in arbitration hearings is the business record exception. A record maintained in the ordinary course of business generally is admissible even if it is hearsay. For example, a production record maintained in the ordinary course of business can be used to show the actual production for a particular day, even if the record is hearsay.

Privilege. Certain types of communications are privileged. Any questions that require the disclosure of privileged communications should not be answered. Communications between an attorney and client are privileged, as are communications between a union representative and a represented employee that arise as part of the representation.

Settlement Discussions/Offers of Compromise. Settlement discussions and offers of compromise are not admissible because admitting such evidence would discourage settlements.

Best Evidence Rule. The *best evidence rule* provides that the original of a document is the best evidence, and without the original, copies may not be admissible. Although copies generally are used extensively at arbitration hearings, you should always have the original available for inspection just in case the other side objects.

Making Objections

To effectively make objections, the presenter must be alert. Objections are properly made before a question is answered. Once the testimony is heard it is hard to "unring the bell." A presenter who objects must be able to state the grounds for the objection—stated with clarity, force, and logic.

Objections can be used for several purposes: to exclude information, prevent undue prejudice, modify the manner of questioning, change momentum, and instruct or calm a witness. The main purpose of objections is to exclude inadmissible evidence. As arbitrators generally will liberally admit evidence, however, the two other most useful goals are to instruct witnesses and break momentum. With "speaking objections" you can give your witness hints on cross-examination (i.e., "I object to the form of the question on foundation because counsel has not shown the witness has any knowledge of this incident"). If the opposing party gets your witness on a roll answering "yes" to questions in quick succession, you may want to object to break the momentum. Be careful with objections, however, because sometimes objections merely highlight harmful testimony.

The most common types of objections are to (1) foundation—has not shown the witness knows, (2) relevance, (3) form—mischaracterizes earlier testimony, and (4) hearsay.

Closing Argument/Posthearing Brief

After all of the evidence is presented, each side is given an opportunity to summarize the case and tell the arbitrator why it should prevail based on the evidence in the record. This may be done in the form of an oral closing argument or a posthearing brief.

If one or both sides want to write a brief, the arbitrator typically will agree unless the CBA's arbitration procedure specifically disallows briefs. The parties then fix a date by which to submit briefs, simultaneously.

If an oral closing argument is presented, the side with the burden of proof usually goes first, followed by the other side, and then the first side gives a short rebuttal. Arbitrators may differ on that procedure, so it is best to ask the arbitrator to indicate his or her preference for the order of closing arguments.

Whether by a closing argument or a posthearing brief, the purpose is to summarize the relevant evidence and apply it to the language of the agreement and arbitral law. Remember to address the canons of contract interpretation discussed above (i.e., past practice or bargaining history). The closing argument or posthearing brief also should be used to punch holes in the opponent's case; that is, why your position makes much more sense, or why the opposition's evidence fails to support its position. It is often helpful to invoke common experience.

Be careful not to assert facts that were not offered into evidence. Particularly if the parties are filing posthearing briefs, one or both sides may be tempted to include recently discovered facts that were not offered at hearing. Such action, however, is improper unless the arbitrator grants a request to reopen the record.

Finally, make a request for specific action on the part of the arbitrator, for example, the company requests that the grievance be denied. If representing the union, ask specifically for the type of relief being sought. In a discharge case, ask that the grievant be reinstated with back pay.

POSTARBITRATION MATTERS

Supplementing the Record

Prior to the arbitrator rendering a decision, either side may request that the record be reopened for newly discovered facts. Arbitrators, however, do not look favorably on such requests, so you must have good cause or compelling circumstances. You generally must demonstrate the extreme importance of the facts, and that you could not have discovered the evidence earlier with reasonable diligence.

The Award

Arbitrators typically render their awards in writing within 30 to 60 days after posthearing briefs were submitted. If the arbitrator sustains the grievance, he or she will provide for a remedy.

If the remedy involves monetary compensation, the arbitrator generally will not order a specific amount, but may order back pay for a specified period. The parties then attempt to calculate an amount consistent with the award. The arbitrator generally retains jurisdiction over the remedy. If the parties cannot agree, they can submit evidence and arguments on remedy to the arbitrator for discussion.

CONCLUSION

Arbitration is very worthwhile as an alternative to litigation, and is used as the last step of the grievance procedure under many collective bargaining agreements. The key to good arbitration presentation is good preparation, and understanding what to expect. In this chapter we acquainted you with the arbitral process and explained some of the key ingredients of good arbitration presentation.

PRESENTING A CASE AT ARBITRATION

FURTHER READING

Elkouri, Frank, and Elkouri, Edna Asper, *How Arbitration Works,* 5th ed., M. Volz and E. Goggin, eds., BNA Books, Washington, DC, 1997. (book)

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BIOGRAPHIES

George J. Matkov, Jr. is a founding partner of the law firm of Matkov, Salzman, Madoff & Gunn in Chicago, which represents management in labor, employment, and benefits law. Matkov has for many years represented companies throughout the United States in complex labor and industrial relations matters. His practice concentration areas include labor contract negotiations, labor arbitration, practice before the National Labor Relations Board, compensation and benefits, OSHA requirements, and Employee Retirement Income Security Act, equal employment opportunity, and related litigation. He is a recognized national expert in the areas of salaried and hourly compensation systems including engineered standards (incentive and measured daywork), gainsharing programs, and job evaluation systems. Mr. Matkov is one of the few labor attorneys in the country who is considered an expert in the employee, labor, contract and compensation issues involved in cellular and just-in-time manufacturing systems. Mr. Matkov is included in the corporate list (management labor law) of S. Naifeh & G. W. Smith, *The Best Lawyers in America* (1st ed. 1983, 2d ed. 1987, 3d ed. 1989, 4th ed. 1991–92, 5th ed. 1993–94, 6th ed. 1995–96, 7th ed. 1997–98), and was included in *World's Leading Labour and Employment Lawyers,* published by the International Financial Law Review (1st ed. 1995–96, 2d ed. 1997–98). Matkov received his law degree from the University of Iowa in 1966, graduating at the top of his class (LL.B.; Order of the Coif).

Jacqueline M. Damm is an associate with the law firm of Matkov, Salzman, Madoff & Gunn. Her practice is focused in the areas of traditional labor, employment, and employment discrimination law. In her traditional labor practice, Damm represents employers in labor arbitration proceedings and before the National Labor Relations Board, negotiates collective bargaining agreements, and counsels employers on labor-management issues. In her years with MSM&G, she has represented employers at hundreds of labor arbitration proceedings, including many proceedings involving engineered standards (incentive and daywork), and job evaluation issues. Damm graduated *cum laude* from the University of Minnesota Law School in 1992, where she was a member of the Wagner (Labor) Law Moot Court.

Source: MAYNARD'S INDUSTRIAL ENGINEERING HANDBOOK

CHAPTER 7.6

COMPENSATION ADMINISTRATION

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This chapter presents an overview of the design process often used to construct one or more administrative structures consisting of a series of related pay grades, ranges, or rates, which guide ongoing employee pay decisions in an organization. The authors describe the need for overall organization policy decisions, various methods for melding external pay rate data and internal job rankings, and several typical practices for establishing pay ranges. Also covered is the design approach frequently used to develop merit increase guidelines and to monitor the administration of a base-pay program.

OVERVIEW

Effective administration of an organization's compensation program is important for several key reasons. First, the direct and indirect costs associated with employing a competent workforce have a significant impact on productivity and, ultimately, on profits. Second, the manner in which a compensation program is developed, maintained, and administered has a direct influence on the level of employee confidence that pay is internally fair and equitable. Third, an organization's compensation practices often are the single most important representation of top management's view of their employees and what the organization values.

ROLE OF BASE PAY

Base pay is commonly regarded as the critical element of a compensation program because it is the most regularly visible aspect of the typical employee's compensation package. Moreover, it is frequently the primary variable used to scale a broad array of other workplace incentives, special reward schemes, benefit plans, and perquisites. Consequently, most organizations having more than a small number of employees, adopt one or more formal base-pay structures to provide guidance for making pay decisions and to institute various administrative controls over current and prospective pay levels.

BASE-PAY STRUCTURES

Base-pay structures are traditionally constructed as a series of fixed hourly pay rates or a set of pay ranges that are successively greater amounts related in some proportional manner to either increasingly greater job requirements or responsibilities and/or external market values. In addition to pay rates that may be the result of bargaining unit agreements, most organizations will have at least two base-pay structures: one for exempt and one for nonexempt jobs. Beyond these, other structures may be instituted depending upon the number of geographic locations where people are employed, and the perceived need to adopt somewhat different pay practices for some employee groups such as top executives, sales personnel, technical specialists, and so forth.

REGULATORY ISSUES

The designation of a job (or the actual duties of an employee) as *exempt* or *nonexempt* is frequently misinterpreted as an indicator of status in the organization. More correctly, the term *exempt* refers to certain provisions in the Fair Labor Standards Act (FLSA) of 1938, as well as in similar legislation enacted by the states. Principally, it means exempt from the obligation that an employee be paid an additional one-half of the regular pay rate for all hours of work in excess of 40 in a fixed work week. The FLSA provides a short series of tests for certain classes of individuals categorized as executive, administrative, professional, and outside sales employees. In 1990, a special provision was added to allow exemption for highly compensated computer systems analysts, computer programmers, software engineers, and other similarly skilled professional workers. The tests generally involve the primary duties and responsibilities and the salary paid to an employee.

Regulatory staff construe the test requirements very narrowly, and though the tests appear straightforward, proper interpretation is often difficult. Misclassifying an employee as exempt can be costly because the employer can be deemed liable for back pay, liquidated damages, and civil money penalties. The burden of proof is on the employer and the claim period is measured backward for two years, or three years in the case of a willful violation, from the date on which a complaint is filed.

Ongoing pay decisions must also remain consistent with a large number of other federal and state regulations that seek to curtail discriminatory practices based on race, color, national origin, religion, sex, or disability. Included among these are the Equal Pay Act (1963), the Civil Rights Act (1964), the Age Discrimination in Employment Act (1967), the Americans with Disabilities Act (1990), and the Family and Medical Leave Act (1993). The design, implementation, and administration of any compensation program must be mindful of all the restrictions that may be imposed by both the federal and state regulations.

ORGANIZATIONAL POLICY

When developing or modifying a base-pay structure, concurrent with cost considerations, management needs to expressly address several pay policy or philosophical issues. This requires deliberating the following kinds of questions:

- How closely does the organization wish to mirror the pay practices of other comparable organizations in the industry and/or in the local or regional labor market?

- To what degree shall direct compensation be fixed in the form of a base-pay rate, and how much, if any, shall be in the form of variable or incentive pay?
- How much will the organization rely upon direct compensation to influence its ability to attract and retain people who have the skills and competencies most needed by the organization?

It is important to devote sufficient time and earnestly seek satisfactory answers to these sorts of basic questions in order to establish the objectives for a compensation program. Otherwise, the organization will not have a firm basis for ascertaining the effectiveness of the program at a later date. As an example, a simplistic though useful statement of an objective could be: "Set the target base pay for lower-paid employees 5 percent above local area median pay rates. Set target base pay for higher-paid employees at 5 percent below median rates and maintain an incentive plan that provides total cash opportunity approximating third-quartile rates in the industry."

BENCHMARK JOB DATA

The first step in the process of designing (or evaluating) a base-pay structure is to ensure that there is a clear understanding of the content of the jobs to be covered by the structure. Normally, this involves preparing new, or updating existing, job descriptions that reflect the current essential duties and responsibilities of the persons assigned the job. Whether reduced to a paragraph or several pages, accurate knowledge of job content remains an important element of the structure design process, as well as the ongoing compensation administration program.

The next step is to gather pay rate data indicating what other employers are paying jobs similar to those in the organization. This is commonly referred to as *market pricing* and typically requires researching the data presented in published compensation survey reports, of which there are many. It is rarely possible nor necessary to market-price all jobs in an organization. Rather, prior to researching survey reports, the organization identifies a set of *benchmark* jobs among the group of jobs included in the pay analysis. These benchmark jobs are those that, more or less, have a broadly understood job content outside the organization. For example, two common benchmarks in an exempt, nonexecutive job group are production supervisor and staff accountant.

The number of benchmark jobs varies with organization size and the nature of additional analyses that may follow. If market data are the sole basis for setting or evaluating pay rates or ranges, including about one-half of the organization's job titles in the benchmark set for "pricing" is usually sufficient. If the market data are to be used along with another, separate process for establishing internal job rank or hierarchy, such as a formal point-factor evaluation plan, then only about one-fourth to one-third of the jobs typically need to be market-priced. In either case, the final set of benchmarks includes jobs that represent the extent of the hierarchy and the breadth of jobs portrayed on an organization chart.

Whenever possible, pay rate data for benchmark jobs is collected from more than one survey source. Individual surveys include different sets of participants, and the pay data are submitted at different times. Consequently, the survey pay rates for each benchmark job are adjusted to a common point in time and reduced to a single consensus rate through either a simple averaging or weighting calculation.

A straightforward estimating process is commonly used to adjust or age the data. Both the surveys used to gather benchmark pay rate data and a number of special surveys report actual and projected pay movement in percentage terms. For example, a representative (annual) figure would be 4.1 percent. This is first divided by 12 to obtain a monthly amount. The monthly amount is then multiplied by the number of months between the effective date of the data presented in a survey, to the month established as the common point of reference for the analysis. In this instance, for a period of eight months, the calculation $\{[(0.041/12) \times (8)] + 1\}$ yields an adjustment factor of 1.03.

As is true for many aspects of compensation administration, selecting benchmark jobs, matching job content among survey reports, and weighting and aging data often require a good measure of judgment along with a modicum of science.

DEVELOPING PAY GRADES

A base-pay structure comprises a series of pay grades (or classes or levels). A pay grade may specify a single, fixed rate of pay or a range of pay considered appropriate for persons having essentially equivalent jobs assigned that grade.

Fixed-Rate Grades

Fixed- or flat-rate structures are most frequently used for workers in production, skilled trades, or lower-level clerical jobs. Organizations adopting this type of structure normally set the pay rate of the grade at an amount that closely approximates the market, or the going rate derived from survey data. It is considered the pay rate that a fully trained, proficient employee should earn. In addition, a separate hiring rate is also adopted in most instances.

The change in pay rate from grade to grade is often relatively small (e.g., 10¢ per hour) but may also be as much as 10 percent. The transition from market-rate data to the pay rate for a given grade usually also involves some rounding to the nearest 5¢, 10¢, or 25¢. For unique jobs or those having little or no reliable market-rate data reported in surveys, the pay rate for the grade is usually determined through a process of subjective judgments base on factors such as skill level, experience, effort, responsibility and working conditions.

While fixed job rate structures are relatively simple to communicate and revise, they provide no opportunity to vary the pay of individual employees in the same job grade. Consequently, organizations which find it desirable to allow at least some variation related to length of service, frequently adopt some form of a step-rate approach.

Step-Rate Approach

A step-rate structure incorporates a series of fixed pay rates within each pay grade. The difference between successive rates, or "steps," may be either a constant or increasing dollar or percentage amount. In any case, the change in an employee's pay from step-to-step is commonly related only to fixed time periods. Figure 7.6.1 illustrates a pay grade comprising five steps, separated by a constant dollar amount.

As with any structure, the step-rate amounts are related to the base-pay levels in the pertinent labor market and the organization's overall pay policy. In this instance, the external average or going rate for jobs in Grade A is \$10.40/hour. The learning period is fairly long, and it often requires a year to attain satisfactory proficiency. Turnover is fairly high, and, as a result, the organization has adopted a probationary period of 120 days. After one year, service time is rewarded in two annual increments of \$0.40. The top rate of \$11.20 approximates the 60th percentile rate paid by other comparable organizations in the local area.

Traditional Grade-Range Designs

Many organizations desire to vary the actual base pay of different employees in a job grade in accordance with each individual's experience, job performance, or service. These organizations often adopt a structure of pay grades, which only specifies a minimum, a midpoint or control point, and a maximum base-pay rate for each pay grade.

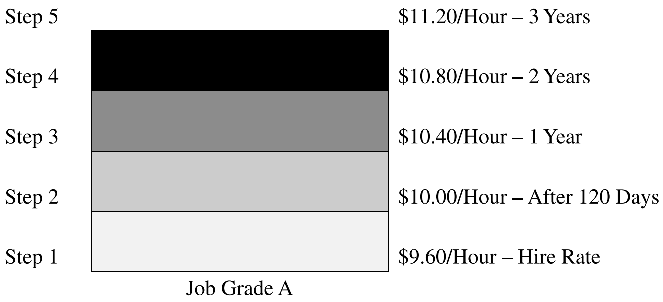

Step 5
Step 4
Step 3
Step 2
Step 1
$11.20/Hour – 3 Years
$10.80/Hour – 2 Years
$10.40/Hour – 1 Year
$10.00/Hour – After 120 Days
$9.60/Hour – Hire Rate
Job Grade A

FIGURE 7.6.1 Step-rate structure.

The midpoint or control point is expressly linked to external pay rates and, as a matter of organizational policy, is the planned base-pay rate for a competent employee. The minimum is the least amount an individual assigned the job grade will be paid. The maximum is the highest pay rate the organization will (normally) allow. The difference between the minimum and the maximum rate of the pay grade is commonly referred to as the *pay range,* or *spread.* Figure 7.6.2 illustrates a typical representation of this traditional, somewhat broader, approach to base-pay structure design.

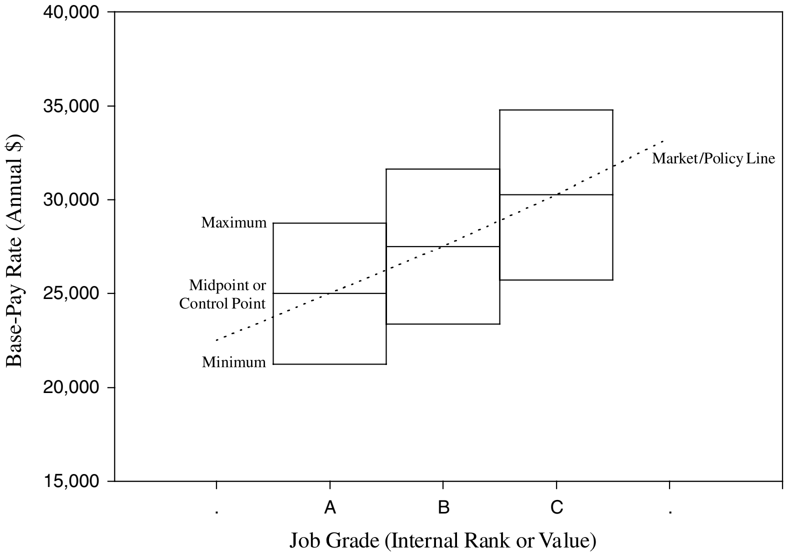


FIGURE 7.6.2 Traditional structure design.

GRADE STRUCTURE DESIGN PROCESS

The process of designing (or revising) a traditional base-pay structure requires a series of concurrent analyses involving market-rate data and the internal ranking relationships among the jobs covered by the structure.

In some organizations, internal rank is derived through formal job evaluation procedures (refer to Chap. 7.2, "Job Evaluation"). In others, the market-rate data for a job or a sample of similar jobs is the primary determinant of internal rank. In either case, there is no correct number of grades. Rather, the number of grades and the dollar values of the grade ranges or spreads are established through a series of trial-and-error steps such as the following:

1. A representative sample of all jobs are listed in rank order.
2. The natural breaks between groups (or families) of jobs are identified. For example, a manager of operations and a supervisor of operations need to be in different pay grades and should have at least one, and preferably two, pay grades between their respective pay grades.
3. A trial set of break points in the internal rankings of the jobs is developed. The jobs may be delineated on the basis of market-rate data alone, or on the basis of an independent internal ranking (i.e., job evaluation) procedure, or a combination of these. Regardless, the breadth of internal rank values (as represented by the *x*-axis in Fig. 7.6.2) is ultimately divided into a series of trial grades.
4. The initial notion of the number of the grades is revised over successive trials until a satisfactory compromise is achieved between:
    - The external pay rates applicable to the jobs in each trial grade
    - The number of levels (or grades) in the organizational hierarchy of all jobs
    - The grade relationships that should prevail among various families of jobs

The central objective of the trials is to develop a systematic, smooth progression from the midpoint value of the lowest pay grade to the midpoint value of the highest pay grade in the structure. The progression may be based on equal or increasingly larger, dollar increments, or on equal or increasingly larger percentage increments between successive pay-grade midpoints. Percentage increments are most common and tend to range between the values shown in Table 7.6.1.

TABLE 7.6.1 Typical Midpoint Progression

Job category	Percentage increment, midpoint to midpoint
Nonexempt	5% to 8%
Exempt	8% to 12%
Executive	10% to 20%

Range Spreads

Once a suitable set of grade midpoints has been developed, the minimum and maximum pay-rate values for each grade are determined. These are usually symmetrical about the midpoint; however, the range spread from minimum to maximum may not be the same for all grades in the pay structure. For example, the range spread may be set at ±15 percent of the midpoint for lower-paid jobs, at ±20 percent for higher-paid jobs, and at ±25 percent for executive jobs. Alternatively, the range spread may be successively larger for each higher grade midpoint (i.e., ±15.0 percent for grade A, ±15.5 percent for grade B, ±16.0 percent for grade C, etc.).

Which range spread design is most appropriate for an organization depends upon the following kinds of factors:

- The expected time required for an employee to attain proficiency in the job
- The extremes in external/market-rate data (e.g., from the 25th percentile rate to the 75th percentile rate)
- The actual opportunity over time for upward movement in the organization and/or the prevalence of lateral movements between jobs or functions
- The number and concentration of longer-service employees
- The impact on gross payroll
- The differential (or incremental progression) between successive grade midpoints

The interplay between the grade-to-grade differential noted in the last factor of the preceding list and the range spread is a key design issue. If the maximum of one grade is equal to or very near the minimum of the next higher grade, there will be little or no overlap between the two grades. Most organizations find this to be an unacceptable situation because it implies that a top performer (and/or a longer-service employee) paid at the maximum of the lower grade is on par with a new hire, or untrained person paid at the minimum of the next higher grade. Conversely, if there is a significant amount of overlap between adjacent grades, it is likely that the distinction between successive job grades is too refined and the structure may be setting forth more grades than the organization really needs. Ideally, an effective structure will have the midpoint of a lower grade near the pay rate half way between the minimum and the midpoint of the next higher grade. In this way, a person at the midpoint of the lower grade, upon advancement to the next highest grade, would have a pay rate somewhat below the new grade midpoint (and the expected proficiency associated with that grade).

MULTIPLE BASE-PAY STRUCTURES

Many organizations have both exempt and nonexempt employees at the same location or in a particular geographic location. Base pay in this situation is often administered in accordance with two pay structures—one for exempt and one for nonexempt jobs. The structure designs may either abut or overlap. Either way, the juncture between the two structures also requires a specific analysis to ensure that the organization is not faced with inconsistent guidelines for administering pay. The base pay for a higher-level nonexempt employee may be less, but can and often does exceed the base pay for a lower-level exempt employee. Regardless, in addition to total direct pay and fairness issues, it is important to examine what can occur under various scenarios of advancement from a nonexempt position to an exempt position—and therefore, from one pay structure to another.

ADMINISTERING EMPLOYEE PAY

A salary structure sets forth the rates of pay the organization plans to provide different jobs. However, determining how much will actually be paid an employee depends upon both the type of structure design and a number of additional policy alternatives governing pay decisions. Some of the alternatives are straightforward and relatively simple to administer. Others require consideration of multiple factors, including individual employee performance, and can be fairly complex to administer.

With a fixed- or flat-rate structure, relatively little policy guidance is necessary because there is one, and only one, rate of pay for each job, and the pay rate changes only when the employee is assigned a job that has a different pay rate or when the entire structure is revised.

With a step-rate structure, the primary determinant of an employee's pay rate is time in the job. Typically, beyond a probationary period, the employee's pay rate is automatically increased to the next step in the pay grade upon completion of each year of service. Nonetheless, the organization needs to determine what should be done in the event an employee is promoted. In general, the employee's pay rate/step in the new grade should be greater than the step rate being paid the employee in the old grade. Some organizations formally specify which step in the new grade will be applicable. Others have policies that state that the new step shall approximate the rate resulting from applying a particular percentage to the employee's current rate for each grade between the new and the prior grade.

An important disadvantage of the annual, automatic, one-step increase policy is that it does not provide supervisors a means for recognizing the performance level of individual employees. Where such flexibility is desired, organizations adopt policies that either (1) allow the time period between pay increases to vary (i.e., good performance may be recognized with an increase at times other than year-end), or (2) allow performance level to indicate the number of steps that may be included in a single pay increase (i.e., good performance, one step; excellent performance, two steps; etc.).

Another policy alternative is to use the annual, automatic step increase concept up to that step that represents the midpoint or job rate of the grade. Thereafter, individual increases are based on merit alone.

Skill-Based Pay

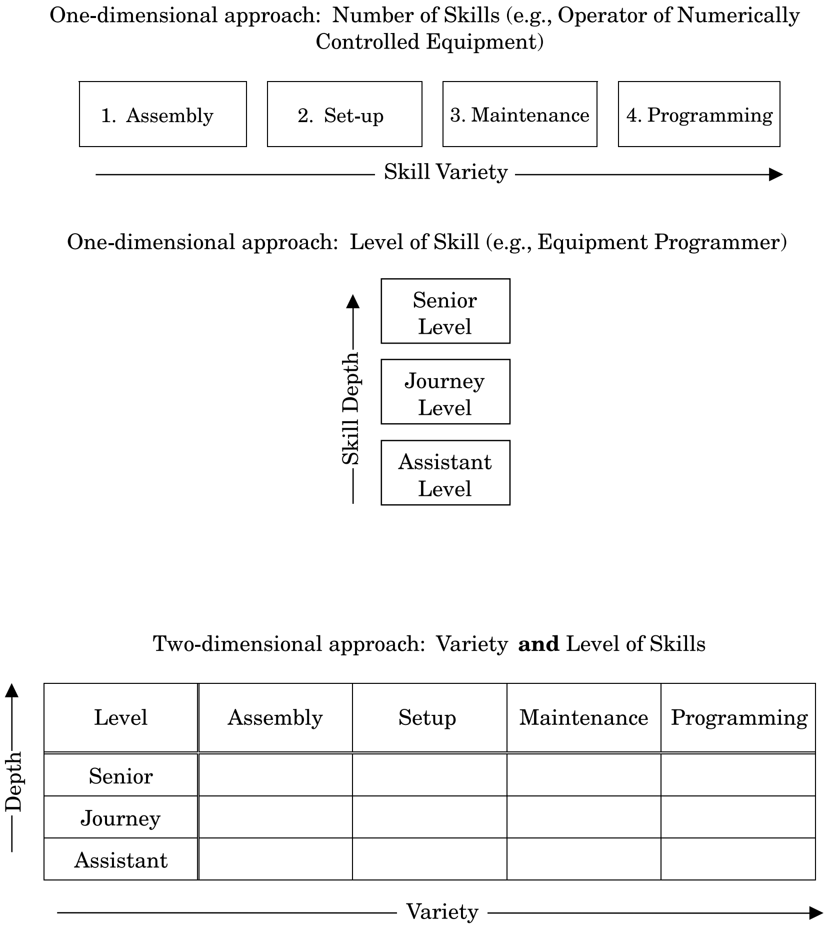
A number of manufacturing organizations undergoing significant change, new growth, or radical process modification have adopted pay administration policies that focus on the demonstrable skills of individual employees rather than whole-job content. In other words, workers are paid for the skills or knowledge they have attained and use, instead of solely on the basis of the job they hold.

Under these skill-based pay approaches, specific skills or sets of skills are linked with a specific pay level, not unlike the succession of rates in a step-rate structure. The traditional notions of length of service and experience are deemphasized, and virtually all pay increases are the result of a formal determination that an employee has mastered certain skill sets. For example, an employee who has become proficient at completing a particular set of routine assembly tasks would be paid $10.00 per hour. Upon mastering another set of more complex assembly tasks, the employee's pay would be advanced to $12.00 per hour, and, after learning all aspects of setup for the assembly operations, pay would be advanced to $14.40 per hour.

Establishing a skill-based pay structure requires a series of analytical steps and policy decisions such as the following:

1. Identification of the set of skills that a proficient employee must have
2. Specification of criteria that shall serve as a credible basis for a certification or mastery test of one or a cluster of skills
3. Development of the process that will be used to determine the level of skill mastery, including who will administer the test procedure, when will it be scheduled, and what standards will be used
4. Determination of the internal relative value of each skill . . . in terms of pay dollars
5. Preparation of other specific administrative policies governing the evaluation of skill currency, the manner in which new or obsolete skills will be factored into the process, when will pay-rate changes (up or down) become effective, and the like.

There are three basic approaches to identifying and defining the skill sets, which will form the foundation of a skill-based pay structure, as illustrated in Fig. 7.6.3. Employee pay may be derived from the number of skills mastered. Or, the pay may reflect the level or depth of skills mastered. Or, the pay may recognize both the number *and* the depth of skills mastered. In this last, two-dimensional approach, a point system is commonly used to determine pay increments.



One-dimensional approach: Number of Skills (e.g., Operator of Numerically Controlled Equipment)

One-dimensional approach: Level of Skill (e.g., Equipment Programmer)

Two-dimensional approach: Variety **and** Level of Skills

Level	Assembly	Setup	Maintenance	Programming
Senior				
Journey				
Assistant				

FIGURE 7.6.3 Skill identification approaches.

For example, if skills can be acquired in four different areas, each having three levels of expertise, an employee could earn up to 12 points (i.e., one point for each level of each skill area); if some skill areas have only one or two identifiable levels of expertise, it would only be possible to earn one or two points in those areas. Also, if higher levels of expertise warrant larger pay increments, or if some skill areas are more valuable than others, it is possible to assign higher point weightings to these.

Organizations instituting a skill-based pay structure need to be wary of making the process unduly complicated. This invariably leads to high administration costs. It also increases the prospect that the concept will be difficult for employees to fully understand and, as a consequence, limit the degree to which the organization can achieve the primary objective—employee skill development and mastery.

There are three particularly challenging issues inherent in skill-based pay systems. First, a significant expenditure for training is required. This includes the time required to develop training programs and to administer certification procedures as well as the cost of an employee's lost productive output while undergoing training. Therefore, the organization needs to make a firm commitment to spend the time and money to make training available on a continuing basis over the long term.

Second, considerable controversy can, and usually does, arise with regard to the fairness and credibility of the certification procedure, particularly when there are a large number of complex skills involved.

Third, over time an organization may end up with more employees certified at the highest skill rate than necessary to fulfill day-to-day operating requirements. Although this allows greater flexibility in the assignment of individual employees to scheduled work, it also means that the (high) pay provided some employees will exceed that warranted for completing tasks that have a lower skill level requirement. In turn, this can lead to higher payroll costs for a given level of output. To control this pay escalation, some organizations adopt a "use it or lose it" policy (i.e., employees who have not been afforded the opportunity to utilize the highest skill level for which they are certified for a specified length of time are automatically reduced to the pay rate applicable to the skill level required of the most recently completed or currently scheduled work). Clearly, this type of policy requires considerable attention to procedural details and an especially good communication program, outlining the rules for assignment to and/or recertification for higher skill-level work.

Knowledge-Based Pay

Knowledge-based pay systems for administering compensation are similar to skill-based pay concepts in that both relate the pay rate to what an individual knows or has mastered. However, rather than linking pay rates to an internal certification process or test, knowledge-based pay concepts rely heavily on authentication by an external body. For example, a bachelor's degree in engineering conferred by a university attests to a certain level of skill and ability attained by an individual in a particular field, and a company needing this sort of knowledge will provide that individual a specific rate of pay. Similarly, an individual who has earned a master's degree will be afforded a different rate of pay.

Use of an external certification has been a popular approach for professional positions for some time. On the surface, it may appear that the knowledge-based pay-rate determination process is no different than the more traditional job content systems. Nonetheless, it is important to remain aware that the pay rate, at least initially, is directly related to a presumed level of skills and abilities that an individual brings to the organization rather than the expectations associated with a specific job (title) or current work assignment.

Merit-Based Pay

Merit-based pay refers to various approaches to base-pay rate adjustments in which individual job performance is a key determining factor. Typically, the organization maintains a pay structure similar to that illustrated in Fig. 7.6.2 (i.e., a series of pay grades, each with a minimum, midpoint, and maximum rate). In addition, a credible performance appraisal system needs to be in place.

The effectiveness of a merit-based approach depends upon a number of factors. First, employees must have some discernable level of control over their performance on the job. Should this element of control be absent, as is the case with jobs that are a composite of rigidly designed, unvarying tasks, the alternatives for pay adjustment revert to service time, attendance, and other similar factors. In these situations, across-the-board, cost-of-living, or another form of granting a fixed increase amount for all incumbents is a common and more appropriate approach. Second, it must be evident that the organization has a reasonably objective and consistent procedure for measuring and rating performance. Otherwise, employees will likely conclude there is no link between performance and pay, and ultimately perceive merit-based pay as a less-than-truthful program. Third, management needs to clearly communicate that above-average performance is important and to follow through by budgeting sufficient dollars to support meaningful base-pay increases—to at least some portion of the workforce. When each of these conditions is met, a base-pay increase program can be an effective means for motivating individual employees and for retaining better performers.

Merit Increase Factors and Guidelines

Merit-based pay programs commonly use one or a combination of three factors to guide pay increase decisions. These include (1) the performance rating of the employee, (2) the location of the employee's pay rate in the assigned grade range, and (3) the time interval between pay increase/performance evaluation decisions.

In the most straightforward approach, the performance rating is the sole determinant of the pay increase amount. Table 7.6.2 illustrates this type of guideline. It provides for a single percentage increase amount at each performance level, but can also stipulate a narrow range of allowed increase (i.e., 3.5 to 4.5 percent at "competent," instead of 4.0 percent).

TABLE 7.6.2 Merit Increase Guideline—One Variable

Performance rating	Merit increase percent of base-pay rate
Outstanding	8.0%
Above average	6.0%
Competent	4.0%
Marginal	2.0%
Unsatisfactory	0.0%

To maintain control over total compensation costs, some organizations limit the percentage of employees that may be rated at each level of performance in a particular department or unit (e.g., no more than 10 percent at "outstanding," no more than 20 percent at "above average," etc.). Instituting this sort of forced distribution of performance ratings also serves to decrease the tendency to first select the merit increase percent and then develop supporting documentation to justify the performance rating—in direct opposition to the fundamental objective of performance appraisal programs. Managers of smaller departments or units often find the forced distribution constraints particularly troublesome. Where there are only a few employees, each honestly rated "above average," forcing a range of varying pay increases will be perceived as unfair and inequitable. Consequently, some exceptions to the overall merit increase guidelines are usually required.

Another approach to providing guidelines for adjusting base rates is shown in Table 7.6.3. As indicated, these guidelines utilize both the employee's performance rating and the location of the current base-pay rate in the assigned pay-grade range. In essence, this approach reflects a philosophical or policy decision to (1) accelerate the rate of increase of better performers up to the midpoint rate of the grade, and (2) to slow the growth in base pay once the

TABLE 7.6.3 Merit Increase Guideline—Two Variables

	Location of base-pay rate in assigned pay-grade range			
Performance rating	First quarter	Second quarter	Third quarter	Fourth quarter
Outstanding	8.0% to 9.0%	6.0% to 7.0%	4.0% to 5.0%	3.0% to 4.0%
Above average	6.0% to 7.0%	4.0% to 5.0%	3.0% to 4.0%	2.0% to 3.0%
Competent	4.0% to 5.0%	3.0% to 4.0%	2.0% to 3.0%	1.0% to 2.0%
Marginal	1.5% to 2.0%	0.0%	0.0%	0.0%
Unsatisfactory	0.0%	0.0%	0.0%	0.0%

Minimum Midpoint Maximum

midpoint value has been exceeded. Although the dollar amount of an increase of a higher-paid employee receiving a low-percent merit award may equal or exceed that of a lower-paid employee receiving a higher-percent merit award, managers often find it difficult to accept the notion that a top performer is allowed a lower-percent merit award (and vice versa). Nonetheless, ultimately managers do concede the fact that the midpoint value is the agreed-upon, competitive rate of pay for a job, and that there is a limit to the base-pay rate that can be paid to the incumbent of a particular job, notwithstanding performance level and/or years of service.

There is no one correct set of percentage values to be used in the cells of Table 7.6.3. Rather, the percentages are developed by means of a series of what-if trials reflecting both the compensation philosophy of the organization and the potential impact of one or another set of cell values on the (fixed) compensation expense budget. Typically, the initial set of cell values builds upon a presumed increase percentage in the aggregate base compensation budget (e.g., 3.5 percent). This percentage is commonly placed in the cell representing a competent performer whose base rate is in the second quartile of the pay range. From that cell, other trial cell percentages are developed by adding or subtracting whole or one-half percentage values. In Table 7.6.3, the "Above Average" cell value in the second quarter is set at 1.0 percent above the 3.0 to 4.0 percent figure in the "Competent" row, and the "Outstanding" cell value at 2.0 percent above. Other cell values are inserted in a similar manner.

For a smaller group of employees, when recent performance ratings are known (and/or have been fairly stable), completing the calculations indicated by a trial matrix of cell values using software spreadsheet procedures quickly yields the estimated impact on compensation expense. For a larger group of employees, when only the recent distribution of performance ratings and the distribution of employee base rates in the respective ranges is known, the sum of the cross-products of the row and column distribution percentages for each cell and the merit percent value in a cell can be used to estimate the budget impact. For example, if 5 percent of the workforce is rated "outstanding" and 10 percent are in the first quarter and the cell value is 8.5 percent, then the contribution of this cell to the aggregate increase estimate is 0.0425 percent. Repeating the calculation for each cell, adding the results and applying the resulting percentage to the total of current base-pay rates under consideration will provide a reasonable estimate of the dollar value of the anticipated increase in compensation expense.

A third approach to merit increase guidelines incorporates the concept of variable time periods between base-pay adjustments. As illustrated in Table 7.6.4, rather than a single time period, the time lapse between pay reviews for persons paid high in the range is extended to 15 or 18 months, and that for some better performers paid low in the range is reduced to nine months. Again, philosophical issues influence the merit guideline design. Organizations that have an unwavering policy that pay rates shall not exceed the maximum of the pay range and yet desire to give larger (percentage) increases while slowing pay growth toward the maximum, in many instances adopt this form of merit increase guideline. Similarly, this approach may be used where there is a strong emphasis on good performance for newly hired or promoted employees and an early pay increase is viewed as an effective motivator.

COMPENSATION ADMINISTRATION

TABLE 7.6.4 Merit Increase Guideline—Three Variables

	Location of base-pay rate in assigned pay-grade range			
Performance rating	First quartile	Second quartile	Third quartile	Fourth quartile
Outstanding	8.0% to 9.0% (9 months)	6.0% to 7.0% (12 months)	4.0% to 5.0% (15 months)	4.0% to 5.0% (18 months)
Above average	6.0% to 7.0% (9 months)	4.0% to 5.0% (12 months)	3.0% to 4.0% (15 months)	3.0% to 4.0% (18 months)
Competent	4.0% to 5.0% (12 months)	3.0% to 4.0% (12 months)	2.0% to 3.0% (15 months)	2.0% to 3.0% (18 months)
Marginal	1.5% to 2.0% (12 months)	0.0%	0.0%	0.0%
Unsatisfactory	0.0%	0.0%	0.0%	0.0%

Minimum Midpoint Maximum

Many organizations use one or some combination of the concepts underlying the preceding three approaches. Generally, they are most effective in organizations that have a keen desire to recognize and reward individuals whose work performance can make a markedly different contribution to the achievement of business objectives. Conversely, merit-based approaches are difficult and time consuming to develop and maintain. This is especially true with regard to establishing credible and reliable measures of individual performance.

ADDITIONAL PAY ADJUSTMENT ISSUES

Once a pay structure has been adopted, there are a number of additional compensation management issues that need to be addressed. These are reviewed in the following paragraphs.

Pay Increase Timing

There are two basic approaches to the timing of increases. Either all increases are granted on the same date (commonly termed a *focal-* or *fixed-point policy*), or increases are granted on the anniversary of the employee's hire or promotion date.

Adopting a common date for all increases helps ensure that pay decisions are handled on a consistent and equitable basis because all pay rates and proposed increases can be scrutinized at the same time. In addition, setting the common date shortly before or after the end of a fiscal year improves the certainty of the cost and/or budgetary impact of the pay increase actions. From a particular manager's perspective, however, it can be especially challenging to review and document the work performance of all subordinates in what is often a very compressed time frame. Not only might the appraisal preparation process become rushed, but the time allocated to actually discussing performance with individual employees may be all too brief.

Distributing the pay increases in accordance with anniversary dates allows managers the opportunity to devote more time to review, summarize, and discuss the work performance of each subordinate on an individual basis. This allows for more thorough discussion of the employee's development and career plans, as well as the linkage between pay and performance. Conversely, it can be more difficult to make comparisons among employees and to integrate pay increase actions into financial-planning processes.

Neither approach is right or wrong. Rather, the choice between the two depends on the organization's culture, human resource strategy and planning objectives. In some organizations, completion of an employee's performance evaluation and any pay increase actions are scheduled at different times (e.g., six months apart). In this way, it is felt that the discussion of performance is less apt to be sidetracked by a preoccupation with the prospect of a pay increase.

Promotions/Demotions

The most common definition of a promotion is an upward movement from the current pay grade to a higher pay grade. Promotions within a career family of jobs commonly involve a change of one grade (e.g., from Programmer A, grade 10, to Programmer B, grade 11). Promotions to jobs that include different, significantly greater responsibilities frequently involve a change of two or more grades (e.g., from Senior Engineer, grade 15, to Manager, Manufacturing Engineering, grade 17).

In either case, most organizations provide a separate promotion increase concurrent with the effective date of the promotion. As a general rule, the amount of the promotion increase is in the range of one-half of the percentage differential between the midpoints of the pay grades in the relevant section of the pay-grade structure. In the case of a promotion from a grade with a midpoint of $60,000 to a grade with a midpoint of $75,000, this infers a promotion increase of 12.5 percent. However, several additional factors are usually considered prior to ascertaining a final increase amount. First, the location of the new pay rate in the new pay-grade range is determined. It should be above the minimum rate of the new range and, ideally, somewhat below the midpoint. If the new pay rate is below the minimum, the promotion increase amount would be adjusted upward. If the new pay rate is very high in the new pay-grade range (say, in excess of the third quartile), it would be appropriate to adjust the promotion increase downward. Second, the organization's policy regarding merit increases at the time of promotion may also condition the promotion increase amount. If the organization reviews pay rates on an anniversary date cycle and more than a few months have passed since the promoted employee's last merit increase, a prorated merit increase amount may be granted concurrent with the promotion increase and may lead to a revised promotion increase amount. If merit increases are only considered at a fixed time each year (i.e., a focal-point policy), the merit increase for an employee promoted at midyear may in some organizations be derived from a combination of the performance rating, the pay rate, and pay-grade range in effect prior to and after the promotion date—again, prorated. In turn, the resulting merit increase that would likely be granted at year-end can lead to a revised promotion increase amount.

It should be noted that some organizations have a policy that restricts the effective date of promotion increases to relatively few times during a year (e.g., the first day of the first payroll period of the fiscal quarter). Consequently, in some situations, the promotion increase amount may be adjusted to recognize the elapsed time between the date the promoted employee takes on the new responsibilities and the effective date of the promotion (and/or merit) increase.

By definition, a *demotion* is a movement to a pay-grade range that has lower values than the prior assigned pay grade. The pay actions an organization may take, if any, normally depend upon the circumstances leading to the demotion. If substandard work performance is the reason for the demotion and the employee's current pay rate is less than the maximum of the new, lower grade, it is likely that the employee's pay rate would not be reduced. Should the current pay rate be in excess of the new maximum, it is likely that the employee's pay rate would be reduced to either the new maximum, a specified percentage below the new maximum, or to a pay rate that places the employee in the same relative location in the new, lower grade as in the prior, higher grade (e.g., keep the employee's rate at the 60th percentile location in the grade range).

If the demotion is actually a reassignment to a lower grade due to restructuring, delayering, or some other form of workforce reduction over which the employee has no control, and the employee's pay rate is in excess of the new, lower-grade maximum, the current pay rate is most often frozen. In other words, the rate remains unchanged until such time as the pay-grade structure moves upward to a point where the employee's pay rate is again within the assigned pay-grade range and a normal merit increase adjustment can be made.

Clearly, demotions are difficult situations and most organizations prefer to handle each instance on an individual basis rather than institute any inflexible policy mandates.

Lump-Sum Awards

Organizations with low turnover in various jobs, at times, find that the pay rate of a number of employees is very near or at the maximum of the assigned grade range. Rather than granting a very small merit increase amount or waiting until the overall pay structure is adjusted upward, some organizations provide lump-sum awards to selected employees. This form of award does not add to the base-pay rate and, therefore, does not permanently increase fixed compensation costs. Also, the location of the employee's base pay in the grade range does not change. In the most straightforward approach, the lump-sum amount is made equal to the annualized amount of what would otherwise have been a merit increase in the base-pay rate. Some organizations provide a lesser lump-sum amount reasoning that an award made all at once need not be as large as the (typically, year-long) stream of additional pay resulting from a normal merit increase. Still, others have a practice of granting a combination of a normal merit increase and a lump-sum award at the same time, in some situations. Regardless of approach, lump sums need to be awarded on a selective, solely discretionary basis and should not become standard practice for circumventing normal merit increase policies and guidelines. The fundamental purpose of the lump-sum concept is to provide a reward to better performers who are otherwise ineligible for a merit increase, not to serve as a primary method for cutting costs.

The Compression Dilemma

Among compensation professionals, the term *compression* is used to denote a situation in which the pay rates of two (or more) employees are deemed to be too close together. Commonly, this occurs (1) when pay rates in the external marketplace have escalated and the pay differential between new hires and longer-service employees is no longer equitable, and (2) when the gross pay of overtime-eligible employees regularly approaches or exceeds the pay of their supervisor (who is not eligible for either overtime pay or a bonus award).

Where new-hire pay rates are near or more than the pay rates of longer-service employees in the same job, organizations typically proceed to correct the situation in one of two ways. Either the longer-service employees are granted a fixed or across-the-board pay increase or they are placed on an accelerated schedule of performance/merit reviews (e.g., every four or six months rather than once per year) until such time as successive pay increases create an equitable pay differential.

Where the supervisor-subordinate differential in pay is a continuing problem, organizations will often adopt a policy of providing the supervisor additional pay in the form of straight-time pay for work hours in excess of 40 per week. In situations where the salary of a supervisor is intended to compensate for a few extra hours each week, the same concept is applied with a different threshold (e.g., after 42 hours or after 45 hours).

In any case, the organization is faced with making an often difficult choice between the prospect of losing longer-service, more valuable employees and the certainty of permanently increasing compensation costs.

It should be noted that for some jobs it is not uncommon nor a problem for a subordinate to earn more than a supervisor. For example, among sales positions that are provided a low base pay but have a high-upside-earnings potential driven directly by sales/marketing success, subordinates may be expected to demonstrate exceptional performance and earn significantly more (at least on occasion) than their manager.

Also, there are a number of job families that, for individual development and pay purposes, are viewed as having dual career tracks or organizational ladders. These include engineers, scientists, and other technical professionals. Typically, the organizational structure provides a common set of initial pay levels for all professional staff in a particular type of job up to a predetermined point. Thereafter, both the pay levels and the career choices proceed on different tracks—one leading to higher, individual contributor roles such as principal engineer; the other, following a managerial path. Under this concept, it is acceptable and even planned that the pay level of an individual contributor can equal or exceed the pay of the employee's (administrative or line) manager.

Other/Equity Adjustments

In addition to compression situations, inequities among employee pay rates may occur for several other reasons. For example, an individual may experience a notable increase in job responsibility beyond the simple addition of one or several tasks, but not to the level at which promotion is justified. Also, a transfer to another location or unit, or a change from an overtime-eligible position to a noneligible position may lead to an inequity. Similarly, there can be a clear, permanent upward trend in external market pay rates for a particular category of jobs other than at the new-hire level. Or, a formal review of current job content may result in an upward change in pay grade.

To accommodate these sorts of special circumstances where normal merit increase practices are not sufficient, many organizations formally adopt an equity increase policy. Typically, equity increases are considered somewhat unusual and often are only infrequently granted. The amount and timing of an increase, if any, depends upon the specifics of each individual case. Usually, the review process is more intensive and often includes the current and past performance of the employee, the pay history over the past several years, the years of service and positions held with the organization, the prospect of and perceived ability to gain new or different skills and abilities, and so forth.

In some organizations, the equity increase policy also stipulates a maximum total amount of increase over a previous one-year period. This is usually a fairly high amount such as 30 or more percent. The purpose of the maximum is to ensure that the cumulative effect of recent and potential near-term increases (for whatever reason) is thoroughly reviewed and does not inadvertently lead to another inequitable circumstance—for the subject employee or other employees. It also encourages spreading the effective date of segments of a large equity increase amount over time and accentuates the need to very effectively communicate to the employee the special nature of the increase action.

BROADBANDING

Many organizations that are challenged with the increasingly critical need to become more competitive and responsive in a global economy radically alter the content of jobs to achieve a flatter, leaner operating structure. This often leads to a significant reduction in the number of levels in the organizational hierarchy and, simultaneously, to fewer opportunities for promotion. In addition, the need for cross-training and the ability to easily and quickly move employees laterally from job to job or unit to unit becomes more pronounced.

During the 1990s, in reaction to this kind of major change, a number of organizations adopted a *broadband* approach to compensation administration. In simple terms, *broadbanding* refers to the concept of collapsing many traditional pay grades into relatively few wide bands that are used to monitor and evaluate pay. For example, what was a set of 30 pay grades is reduced to eight broadbands of pay ranges. More specifically, three to five successive pay grades, each with a range spread of 50 percent from the minimum rate to the maximum rate, are converted into a single, wide band with a range spread of 100, or 200, or more percent.

As a practical matter, where broad pay bands are instituted, fewer official job titles are used, and career progress is far less dependent upon promotional opportunities, because there are fewer possibilities for upward grade-to-grade movements.

Typically, broadband compensation policies focus on pay increase actions that are appropriate and/or permitted for employees who are moved laterally in the organization and on how pay adjustments are to be communicated.

Organizations that find that their overall business objectives require extensive training and development of the workforce and/or have a particular need to emphasize flexibility in moving employees or expanding job responsibilities have found broadbanding to be an effective approach. Conversely, organizations that need to exercise tight control over compensation actions and costs often conclude that little or no advantage will result from converting to wide bands.

TOTAL COMPENSATION EXPENSE

Compensation administration policies tend to be developed and maintained in response to one or another set of circumstances. However, the direct and indirect impact of all policies and practices need to be considered when estimating total compensation expenses. For example, if the sum of base pay for a group of employees is $1 million, the annualized cost of an average four percent merit increase budget is $40,000. To this amount, it would not be unusual to find that promotional and other equity increases add another 1.5 and 1.0 percent, respectively, or a total of $25,000. Moreover, the indirect impact of pay increases on the costs of a number of employee benefits (e.g., life insurance, social security, retirement and savings plans, unemployment insurance, workers' compensation, disability benefits, etc.), frequently will add another 30 percent to the cost of direct pay increases, or $19,500 in this instance. Consequently, the total impact of the base-pay increases in this example is about 8.5 percent, or more than twice the average 4.0 percent merit increase budget.

SUMMARY

There are a number of mechanical analyses underlying effective administration of base-pay structures and guidelines. However, there is also a large measure of judgment and discretion required at the design stage, as well as throughout the actual pay determination and delivery processes. Also, in many instances, the organization's philosophy with regard to direct and indirect compensation is the central reference point for both overall and situational decision making. Consequently, organizations need to continually communicate their compensation policies and practices to ensure that employees remain confident and trust that management's pay decisions are consistent, fair, and equitable.

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BIOGRAPHIES

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CHAPTER 7.7

CASE STUDY: MODERN LABOR RELATIONS: THE ROLES OF INDUSTRIAL ENGINEERS AND UNIONS

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To be successful as a world-class organization, the union of workers must work in partnership with the union of managers toward the achievement of common business goals and objectives. Concerns for employees as people must be balanced with concerns for safety, quality, and productivity. Safety, quality, and productivity are like three legs on a stool. Businesses need all three legs to compete, but in the final analysis, the safety and well-being of the worker must be the primary concern—even, if necessary, at the expense of quality and productivity. Attention to this balancing act will equip organizations with the people, skills, and technology needed to compete in the world-class marketplace of the twenty-first century.

This chapter examines how to develop management and employee relationships with the goal of becoming a world-class organization. Along the way, specific consideration is given to the relationship between *industrial engineers* and *unionized/represented employees* as it once was, as it now is, and as it is struggling to become.

INTRODUCTION

International Truck and Engine Corporation (formerly Navistar International Corporation), with world headquarters in Chicago and 1996 revenues of $5.8 billion, is the leading North American producer of the combined heavy and medium truck and school bus market. The company also is the worldwide leader in the manufacture of midrange diesel engines, ranging from 160 to 300 horsepower.

As part of International's drive to profitably grow its share of the market, the company is engaged in a number of programs and initiatives to improve operating efficiencies and focus on continuous improvements, with the goal of emerging as a *world-class organization* [1].

According to Price Pritchett, 230 companies (46 percent of those listed) disappeared from the Fortune 500 list during the 1980s [2]. In recent years, the Class 8 (33,001+ lb), heavy-duty truck market has become increasingly competitive—not just in North America, but in the global marketplace. The Big Three in Class 8 trucks (Freightliner, Paccar, and International) struggle to

TABLE 7.7.1 Heavy Truck Competitive Market Share—Class 8

	1989	1990	1991	1992	1993	1994	1995	1996	1997	1998
International	23.9	22.9	23.1	21.2	20.6	18.6	18.4	16.7	19.3	18.4
Freightliner	16.1	19.0	22.9	23.1	23.9	24.5	26.3	29.4	28.2	30.7
Paccar	23.7	21.9	21.4	20.7	21.3	21.9	20.5	22.0	21.4	20.8

remain cost-competitive in wages, benefits, and productivity while at the same time satisfying and exceeding the customer's expectations of quality, cost, and delivery credibility (see Table 7.7.1).

More and more, manufacturing businesses like International are embracing new technologies, philosophies, and attitudes that are significantly different from those of organizations and employees in the not-too-distant past. Businesses cannot afford to be content with the status quo; they must continue to drive the progressive changes needed to deliver high-quality goods and services at competitive prices or face extinction.

"Progress requires change; if you never change, you will never progress," observed Miller and Schenk [3]. The traditional model, or the old way of doing business, tended to focus on employees as simply factors of production, extensions of the machinery or equipment they operated. Likewise, the role of the traditional manager tended toward solving technical or machine problems that interfered with quality and productivity. The safety and welfare of the people who operated the machines was secondary.

For the most part, the traditional worker was interested in a good day's pay for a good day's work. Workers were also concerned about benefits, adequate and safe working conditions, and an opportunity to do meaningful work. The traditional manager, on the other hand, was concerned about the survival, growth, and profitability of the company—the key to which was productivity. Today, this traditional philosophy is giving way to the need for and emergence of *world-class organizations*—companies that are able to compete effectively both at home and in the global marketplace.

THE INDUSTRIAL REVOLUTION: 1750–1850

The age of industrialism emerged in England in the second half of the eighteenth century (1750–1840). It spread across Russia in the 1860s and migrated to America over the turn of the century.

Essentially, the age was marked by the invention of machines capable of much greater speed, accuracy, and efficiency than people were able to accomplish doing similar work by hand. Mass production of heavy, bulky commodities gave rise to factories full of machines. People were hired simply to operate and maintain the equipment. The 1800s also witnessed mechanical improvements in agriculture, such as the mechanical reaper invented in 1833 by Cyrus McCormick, founder of the McCormick Harvesting Machine Company—now known as Navistar.

As industrialism flourished, so did the capitalist mentality. Owner-managers became obsessed with windfall profits resulting from increased productivity—so much so that workers were rewarded piecemeal, often regardless of safety and quality. The more the workers produced, the more they were paid. In time, workers were unfairly exploited in the name of corporate profit.

PURPOSE AND EVOLUTION OF ORGANIZED LABOR

Employees (including many children), often worked 12 to 14 hours a day in unhealthy and unsafe working conditions for very low wages. As they became more conscious of their plight, workers began to organize and unite in pursuit of common objectives. Organized labor, for example, spearheaded the drive for public education for every child and the implementation of truancy legislation. Benefits that some might take for granted today (e.g., paid vacations, 8-hour working days, five-day workweeks, pensions, health and welfare protection, grievance and arbitration procedures, equal pay for equal work, and statutory holidays) did not exist on any meaningful scale until unions won them for unionized and nonunionized employees alike.

Since the Industrial Revolution, unions have been advocating the rights of employees throughout a period of rapid and significant economic and technological changes—from a time of no electricity, no automobiles, no television, no computers, and no air-conditioning on through the Great Depression and into our modern electronic era. Space travel, global competition, multi-million- and multi-billion-dollar corporations, labor legislation, human rights, collective bargaining, and national labor unions are now the order of the day.

PURPOSE AND EVOLUTION OF INDUSTRIAL ENGINEERING

During the Industrial Revolution, owner-managers chiefly concerned themselves with mass production in pursuit of profit, much to the chagrin of employees concerned with adequate pay and safe working conditions. There was a great deal that the owner-managers did not understand about industrialism: machine feed and speed, plant layout, inventory control, and most important of all, the people behind the machines—in short, all of the characteristics of today's industrial engineer.

In the United States, the people who helped manufacturing factories develop more efficient work methodologies for increasing output were known as *scientific managers,* the ancestors of the people now referred to as *industrial engineers.* For the most part, the early scientific managers tried to solve the technical or machine-related problems that impeded productivity. Their interest in the employees was merely in selecting the right person for the job; for example, a task requiring heavy lifting would be assigned to someone who exhibited physical strength and endurance.

The scientific managers attempted to increase work efficiency by employing such measures as plant design and layout and time-and-motion studies. By placing machinery and supply materials at strategically determined points on the shop floor, they tried to reduce the amount of time needed to move raw materials to a finished-goods state. Likewise, by analyzing the way in which operators fed the machine relative to its speed of operation, scientific managers strove to achieve optimum machine speeds while eliminating excessive motion used by the operators.

Although early industrial engineers may have known much about the technical, machine-driven workplace, their main handicap stemmed from their inability to see the worker as anything more than an extension of the machine.

THE INDUSTRIAL ENGINEER IN TODAY'S UNION ENVIRONMENT

Industrial engineering plays an extremely important role in running a manufacturing business successfully. To begin with, industrial engineering is concerned with the design, improvement, and installation of integrated systems of people, materials, and equipment. The discipline draws upon specialized knowledge and skill in the mathematical, physical, and social sciences, together with the scientific principles and methods of engineering, analysis, and design. It is the assignment of industrial engineering to enhance improvement in safety, quality, and production, and to manage change toward this end—and to do so with a human touch, respectful of each employee's differing skills, abilities, and ideas. The effective industrial engineer works to balance concerns for quality and production with concerns for people and their safety. In their role as problem solvers, industrial engineers must now look beyond surface mechanics to the knowledge, skills, and experience of the workers.

Much to their credit, industrial engineers have a tremendous system perspective and overall view of the production process that enables them to analyze problems and formulate solutions. Their technical training is essential, but without people skills, solving problems is next to impossible.

THE LABOR REPRESENTATIVE IN TODAY'S INDUSTRIAL ENGINEERING ENVIRONMENT

Likewise, the labor representative has a significant role in running the business responsibly. While workers are expected to perform effectively and efficiently, the labor representative is on hand to serve as an advocate for the employee and to identify problems that interfere with safety, quality, and productivity. Just as industrial engineers have come to realize that workers are no longer part of the machinery but are a largely untapped reservoir of potential, so, too, the labor representatives and the employees they represent must grow in understanding and commitment to the organization's vision, strategic direction, and goals. They need to be, and are, trained in the same tools of the trade as their industrial engineering partners.

BREAKING THE CHAINS OF TRADITION

The need to regain a competitive toehold in a world marketplace driven by rising expectations of quality, demand peaks and valleys, and technological change is compelling management and union leaders to dramatically change their way of doing business. What does this mean? In short, it means that there needs to be an awakening to the reality that management and organized labor can no longer afford to work at cross-purposes, to be on opposite sides of the table, each reacting to the demands of the other.

Job security for all is directly proportional and relative to the company's ability to remain competitive in a rapidly changing global economy. There is still a need to unite management with union to satisfy common objectives for survival, growth, profit, adequate working conditions, fair compensation, and the opportunity to do interesting and meaningful work. The objectives are common; the table is round.

Worthy and admirable goals are not always easily attainable. *Change must be negotiated.* And negotiations will not always lead to mutual agreement. Change is inevitable. It is how we choose to respond to change that will determine success or failure. Who better to be the change agents than today's industrial engineers and union representatives?

MOVING TOWARD A WORLD-CLASS ORGANIZATION

The vision is clear: International Truck and Engine wants to be the best truck and engine company. Being the best means achieving world-class status in the following areas:

- Shareowner value
- Customer satisfaction
- Employee motivation and pride

Knowing how we will arrive at these goals needs to be equally clear. A course of action must be defined and mapped out. At International, we are doing exactly that. It's called *changing the culture* and fostering a *climate for performance* in support of our vision, strategies, and programs. The new culture that is emerging at International is value-centered on the following:

- Respect for people
- Customer focus
- Relentless pursuit of quality
- Speed, simplicity, and agility
- Innovation
- Accountability
- Communication

Respect for People

To be a world-class organization means to respect people, represented and nonrepresented alike. Simply put, engage people. Allow workers to participate, to feel important, to be informed, to feel listened to, and to be empowered to make decisions. These tenets are critical to working relationships built on the skills, experience, and contributions of each employee on the team. For industrial engineers and labor representatives, this means

- Openly sharing the needs of the organization and the individual employee and working toward a win-win situation
- Observing, understanding, and appreciating the circumstances of each other's work environment—the good, the bad, and the ugly—to expedite informed decisions rooted in fact
- Developing an effective approach to identifying and solving problems, inclusive of the skills and experience of those actually doing the work
- Promoting teamwork and *pool assembly* [4] over traditional station assignments
- Educating and cross-training workers in multiple skills so they may rotate jobs

Customer Focus

Customer focus is, perhaps, the most important value and characteristic of a world-class organization. This value speaks to meeting and exceeding the expectations of both the external customers (the person or company buying the finished goods) and the internal customers (those employees who are interdependent on each other to carry out assigned tasks). For industrial engineers and labor representatives, this means

- Getting close to your customers, internal or external, to see and hear them in their environment
- Listening to each other and seeking input and feedback in the search to achieve mutual benefit
- Keeping commitments to one another
- Considering the impact of decisions and actions on each other (leaders seeing the work they supervise and listening to the people doing the work to understand the work and the impact of changes)

In the final analysis, customers are the one and only true source of job security.

Relentless Pursuit of Quality

The world-class organization demands consistent quality and continuous improvement in all products, services, and processes. This entails using measurements to define and measure quality. Most important, it means never being content with the status quo and realizing that the best is yet to come. As Miller and Schenk have observed, "Quality is not a spectator sport" [5]. For industrial engineers and labor representatives, this means

- Complying with International (ISO-9000) and North American (QS-9000) quality standards
- Using statistical quality control methods to identify, prioritize, and correct elements of the manufacturing process that detract from high quality (e.g., reducing defects per unit, decreasing cycle time required to complete an assembly or subassembly, process, and calculating the sigma [6] of a process)
- Identifying bottlenecks and streamlining operations
- Benchmarking the competition and adapting their proven methodologies
- Reengineering work processes and procedures to promote continuous improvement

Speed, Simplicity, and Agility

The world-class organization acts with a sense of urgency and turns on a dime to achieve its goals. Leaner systems of manufacturing are designed to continuously reduce waste, complexity, and bureaucracy. Waste comes in many forms—for example, overproduction, time on hand (waiting), unnecessary stock/inventory on hand, unnecessary motion or material movement, and producing defective goods. As Miller and Schenk point out, "Moving fast is not the same as going somewhere" [7]. For industrial engineers and labor representatives, this means

- Conducting time-and-motion studies to design, define, and redefine job assignments to eliminate waste and enhance efficiency
- Designing a plant layout conducive to just-in-time [8] material delivery and productivity improvements
- Instituting the pillars-of-workplace organization:

  Sifting—identifying only what is required to perform the work and removing all other items from the workplace

  Sorting—establishing a permanent location for everything in the workplace

  Sweeping—cleaning the area completely

  Spic and span—organizing the overall workplace

  Self-discipline—maintaining the standard
- Balancing the line and assigning a fair and equitable distribution of the workload through proper assignments of workers and machines, thus ensuring a smooth production flow
- Implementing ergonomic enhancements to provide operator comfort and ease of job performance
- Adjusting to multiple demands, shifting priorities, ambiguity, and rapid change such as new product introductions, production schedule increases and decreases (as dictated by customer demand)
- Responding with a sense of urgency to problems identified by workers
- Investigating the problem and finding a solution based on the facts
- Fixing problems fast, learning, and moving on

Innovation

For the world-class organization, innovation speaks to the value of creative resource management to champion new and better ideas. New technologies in computers, telecommunications, and robotics continue to intensify worldwide competition. According to Price Pritchett, "The first practical industrial robot was introduced during the 1960s. By 1982, there were approximately 32,000 robots being used in the United States. Today there are over 20,000,000" [9].

Generating innovative ideas and solutions is risky, sometimes resulting in failure. Without a willingness to assume risk, however, organizations will never achieve the breakthrough products, services, and processes needed to achieve world-class status. For industrial engineers and labor representatives, this means

- Empowering employees to generate new ideas and approaches that result in improved safety, quality, and productivity
- Encouraging employees to think and act creatively
- Being a systems innovator, integrator, teacher, leader, and coach
- Seeing setbacks as opportunities for learning
- Cutting through red tape to get things done faster and more efficiently

Communication

The industrial age has given way to the information age. There has been more information produced in the last 30 years than in the previous 5000. Communication technology is radically changing the speed, distance, and volume of information flow. According to Price Pritchett, "In 1991, for the first time ever, companies spent more money on computing and communications gear than the combined monies spent on industrial, mining, farming and construction" [10].

International Truck and Engine, a world-class organization, realizes that there is a direct link between communicating about its business and managing it successfully. In a successfully managed world-class organization, clear and decisive communication channels are in place. Information flows smoothly among all levels of the organization. Employees understand the goals and objectives of the business and how to achieve them. A working environment, based on respect for people and accountability, begins to emerge. For industrial engineers and labor representatives, this means

- Listening to one another
- Sharing information and background that makes an issue meaningful
- Responding, rather than reacting, to situations, incidents, problems, and crises
- Acting in a manner that is professional and exemplary
- Employing modernized information and telecommunication systems (pagers, cell phones, computer software, etc.)

CONCLUSIONS AND SUMMARY

Industries and industrial practices have changed significantly over the past decades. Many companies have come and gone. Hard lessons have been learned at the expense of people, time, energy, and materials. Competition has become global. For those struggling with decades of tradition and adversity, progress toward becoming a world-class organization is slow . . . oftentimes painfully slow. Some can bear it, others cannot; some rise to the challenge of change, and others resist.

In any evolutionary process, two statements hold true:

1. The fittest survive.
2. The fittest adapt to new environments.

In the world-class, postindustrial age, business enterprises will succeed or fail based on their abilities to manage and lead people—for it is people who use assets to achieve goals. Managers and organized labor must embark on a new era of partnership, working together in a way that meets the needs and objectives of both the organization and the employees. In the organization of the twenty-first century, everyone is responsible; everyone is accountable. The table is round.

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BIOGRAPHY

Larry Clement began his career with Navistar International in 1973 as an industrial engineering supervisor. His career spanned a period of 25 years, and he retired from the position of Director, Manufacturing Support for International's Truck Manufacturing Operations in 2000.

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SECTION 8

FACILITIES PLANNING

Source: MAYNARD'S INDUSTRIAL ENGINEERING HANDBOOK

CHAPTER 8.1

A QUANTITATIVE APPROACH TO THE SITE SELECTION PROCESS

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This chapter describes a new comprehensive approach for strategically selecting a new site for an organization. The approach allows decision makers to effectively match their organization's objectives and goals with the financial considerations of a new location.

The process of choosing a new location is much like that of any other business decision. First, management assesses the relative importance of the factors or attributes on which alternatives are to be evaluated. Second, management evaluates the attractiveness of the attributes of each alternative location, and finally, combines the attributes into an overall assessment of each alternative. Decision scientists can model this complete process to arrive at a list of best options.

Many Fortune 500 firms in making the site selection or relocation decision have formally applied this model. The model is able to answer the hard financial questions as well as the soft issues of selecting new sites in a single "apples to apples" comparison. The financial cost-benefit is only the first phase of the overall site selection methodology. In the final phase, other site selection drivers must be incorporated into the decision process, such as transportation infrastructure, labor availability, or any number of quality of life issues.

All of these drivers, including the cost-benefit derived from the first phase, are given weights based on the Analytic Hierarchy Process (AHP). AHP organizes all of the trade-offs among the competing drivers and helps determine appropriate weights to be used in making a final decision.

BACKGROUND

Determining the location of a new site or relocating from an existing site can have an astoundingly large impact on the bottom line. However, to truly assess this financial impact, all direct and indirect factors must be considered in totality. For example, a new site must be consistent with the future direction of the firm, including growth. In the age of the Internet, determining the right site is even more critical because of the growing impact of technology on an organization. Internet technology and the growth of e-commerce affects distribution models (inbound and outbound disintermediation of distributors) and impacts labor because of new work processes such as telecommuting.

Traditionally, site selection decision makers strictly looked at real estate costs as the determining factor. However, potential labor cost savings can be much greater than real estate costs. Additional factors such as proximity to suppliers/customers, when quantified, can also outweigh the real estate cost considerations. A well-structured model can provide real estate managers with a tool to evaluate all the direct and indirect factors in a cost-benefit analysis for site selection, relocation, or expansion.

As corporations implement data warehousing solutions, the data required for effective modeling is more easily available. The increasing use of information technology to gather data for the move, model the move, and generate financial analyses enables managers to make quicker decisions based on sound criteria and wider consensus. One such software model, as discussed in this chapter, is based on a combination of using spreadsheet software with decision-making software.

The spreadsheet model analyzes the one-time costs and benefits associated with relocating to any number of possible sites. These potential sites are presented in a scenario format, each with varying assumptions. Each assumption is flexible so as to provide the user with a "what if" analysis capability. The purpose of the model is to provide site selection decision makers with a matrix of the costs and benefits of each potential scenario relative to one another.

ONE APPROACH TO SITE SELECTION DECISION MAKING

Figure 8.1.1 depicts one approach to selecting a new facility site.

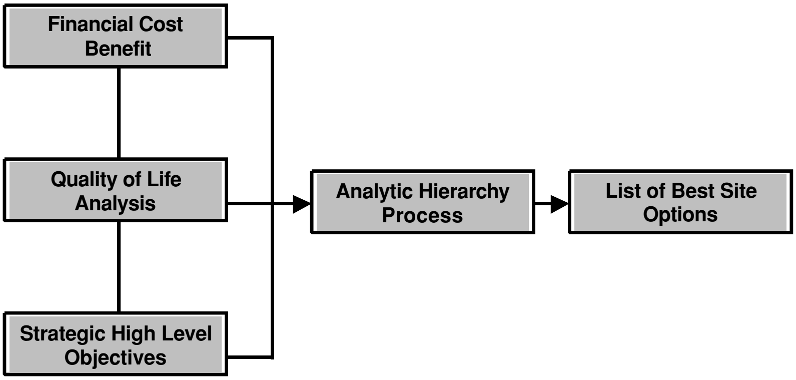
Financial Cost Benefit
Quality of Life Analysis
Strategic High Level Objectives
Analytic Hierarchy Process
List of Best Site Options

FIGURE 8.1.1 One approach to site selection decision making.

Financial Cost-Benefit Analysis

Industrial engineers should focus their attention on analyzing the hard cost/savings of a new location such as real estate, labor, and one-time facility construction costs. Other strategic issues related to the costs of a technology infrastructure, operating taxes, or financing must also be modeled. The critical task is to determine the bottom-line financial impact of the new location over a given time horizon.

Quality of Life Analysis

When discussing quality of life for a corporation, we typically mean the issues facing its employees that maximize work productivity and life balance. In many cases, especially for high-technology firms, where the average age of the worker is in the mid-20s, the weather plays an important role (outdoor activities). Other issues may include the transportation infrastructure available either for employees' commute or for distribution trucking concerns. The most difficult aspect of trying to maximize quality of life objectives is that they are almost impossible to quantify and therefore compare. Comparing the importance of the weather to transportation or crime is handled in the discussion on the AHP technique for making valid comparisons.

Strategic High-Level Objectives

Senior management often has ulterior motives or objectives that need to be considered such as labor quality, proximity to strategic partners, or glamorous zip codes (e.g., Silicon Valley). What often happens in a site selection decision process is that these objectives, often inappropriately, get the highest weighting from senior management. The AHP technique can help put these objectives in perspective with the other criteria without using an arbitrary weighting scheme.

OVERALL METHODOLOGY

The overall methodology discussed in this chapter is based on evaluating a subset of 10 locations that were selected after eliminating the hundreds of potential domestic or international site locations. For example, one could evaluate all 266 metropolitan areas in the United States and narrow the list to the top 10 locations in terms of having available labor resources.*

Once the list is narrowed to 10 locations, a cost-benefit model is applied to determine the one-time costs of relocation, compare them to the anticipated labor, real estate, tax, and utility savings in each location, and then calculate a bottom-line net benefit.

Financial cost-benefit is only one component of the overall decision process. In the final phase, other site selection drivers are examined, including telecommunications infrastructure, transportation infrastructure, and quality of life issues. All these criteria are given appropriate weights using a second proprietary model based on the Analytic Hierarchy Process. Interviews of key business managers should serve as the basis for evaluating the importance of each site selection driver. The goal of the AHP model is to arrive at a list of 2 or 3 final locations.

COST-BENEFIT MODELING

The overall steps to create a cost-benefit spreadsheet model are

1. Obtain necessary data from human resource and facilities managers.
2. Analyze market-level wages for relevant occupations.
3. Analyze lease rates for selected areas.
4. Estimate one-time relocation costs.
5. Conduct long-term cost-benefit analysis of alternative locations.

---

* The list of 266 major metropolitan areas can be ranked in terms of unemployment, projected labor growth, and median wages for the specific labor categories expected in the new facility. These criteria can be weighted to formulate an index ranking of the top 10 locations, which maximize labor availability and minimize labor cost. Labor availability analysis is further discussed in Appendix I.

The information assembled and the analyses conducted in steps 1 through 4 are effectively combined in step 5's cost-benefit analysis. A spreadsheet model is applied to arrive at the cost estimate by integrating the analysis of wage cost differences, one-time relocation costs, real estate cost differences, and productivity impacts of relocation (see Fig. 8.1.2).

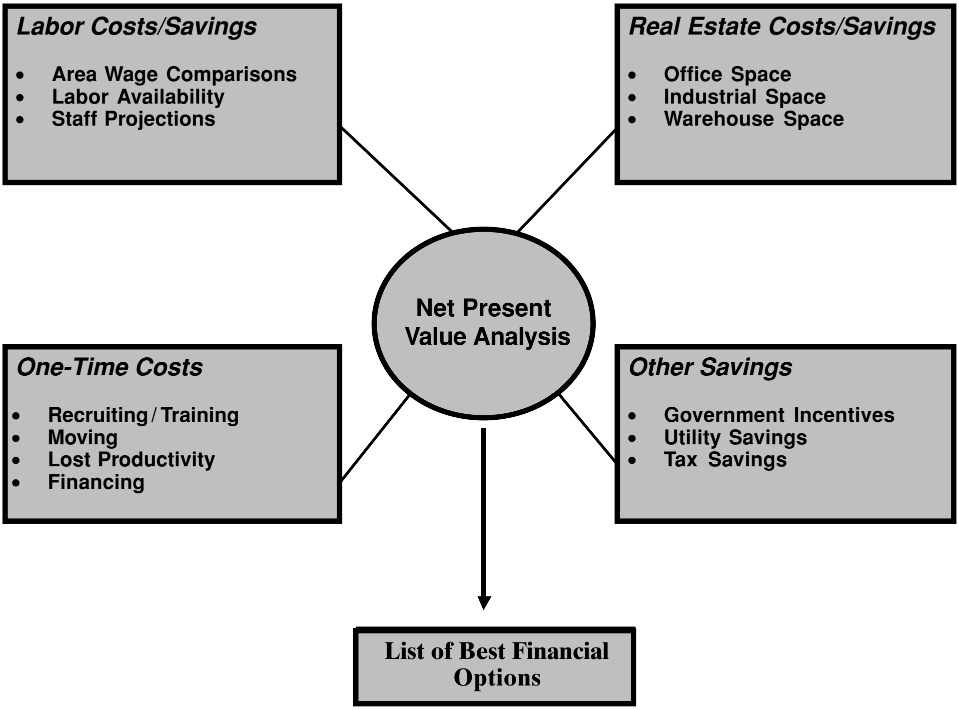
Labor Costs/Savings
• Area Wage Comparisons
• Labor Availability
• Staff Projections
Real Estate Costs/Savings
• Office Space
• Industrial Space
• Warehouse Space
Net Present Value Analysis
One-Time Costs
• Recruiting / Training
• Moving
• Lost Productivity
• Financing
Other Savings
• Government Incentives
• Utility Savings
• Tax Savings
List of Best Financial Options

FIGURE 8.1.2 Overview of cost-benefit modeling.

Size and occupational composition of workforce—current size of the staff categorized by labor category: exempt, nonexempt, technical, and executive

Wages and benefits

- Average salary by labor category (exempt/nonexempt)
- Detailed listing of positions with wage and years of experience
- Benefits package paid to each labor category, including expected severance pay and outplacement fees

Past recruiting activity—Length of time it typically takes to fill positions

Past attrition rates—Historical employee attrition rate by labor categories

Replacement hiring costs—Historical recruiting costs such as advertising, contract recruiter, agency/search, and physical/drug tests

Projected growth of workforce—Estimate of staff and position growth rates or forecasts based on market data relevant to the industry

A QUANTITATIVE APPROACH TO THE SITE SELECTION PROCESS

Current and projected space requirements for office/industrial space—Estimate of future space needs or a forecast of space requirements based on employee growth

Employee moving costs

- Percentages of homeowners versus renters
- Estimate of employee retention per labor category once a decision to move is announced

*Overhead costs**

- Existing utility rates for electric, water, gas, refuse disposal, and so on
- Tax rates for property and sales taxes

SITE SELECTION COST ANALYSIS

The major objectives of the cost analysis include

- Analyze the one-time costs associated with moving from the present location to any of 10 sites.
- Compute the relevant cost savings attributed to the new location over the course of 10 years for each site.

Methodology

A spreadsheet model should be developed to analyze the one-time costs associated with moving the firm from its present location to any number of possible sites. These potential sites are presented in a scenario format, each with varying assumptions so as to provide the user with a "what if" analysis capability.

The purpose of the model is to provide decision makers with a matrix of the costs and benefits of each potential scenario relative to one another. Although all costs and benefits are not detailed to their absolute values, they are valuable to the decision maker for comparison of scenarios on a relative basis. The spreadsheet cost model will not incorporate qualitative factors such as crime rates, educational standards, or climate. These factors can be quantitatively added to the model at later stages of the decision-making process using the AHP.

The analysis of one-time relocation costs comprises the following components:

- Recruiting costs
- Incentive pay to stay costs
- Severance pay costs
- Training costs
- Dual operation costs
- Employee and equipment moving costs
- Financing costs

These costs are generally the most recognized in terms of having a major impact on the relocation decision, and usually vary greatly across different scenarios because of the assumptions underlying each scenario. In comparison with the one-time relocation cost analysis, the model should conduct an analysis of the wage, real estate, tax, or utility savings for each of the scenarios. For example, average wages for similar relocating positions included in each scenario are indexed against the benchmark scenario to reflect labor cost savings.

---

* Several costs could be included here. See the Conway McKinley reference for a more thorough checklist of cost criteria.

The net present value (NPV) of the total savings in each year over a 10-year horizon (or variable time horizon) is calculated using a discount rate appropriate to the individual company. Each year's cumulative present value savings for the scenario is then compared to that scenario's total one-time relocation cost. Since the savings have been discounted to a present value for the year of relocation, a useful comparison can be made. The year in which the cumulative net benefit becomes zero or positive is considered the break-even year, that is, the year in which one-time relocation costs are recouped.

The Cost-Benefit Framework

The cost-benefit framework can be stated:

$$\text{NPV}\ [(A_1 + \textstyle\sum_{1..n} B) - (\textstyle\sum_{1..n} C)] = \text{Net Benefit (Y2001 \$)}$$

where A = one-time setup costs (incurred only in year 1)
B = ongoing annual costs (incurred from year 1 to n)
C = financial benefits or cost savings (incurred from year 1 to n)
$\sum$ = summation over years 1 to n
NPV = net present value in year 2001 dollars

NPV is defined as the difference between the discounted present value of benefits and the discounted present value of costs. It is a discounted cash flow method of investment evaluation that incorporates the time value of money into the capital budgeting analysis. NPV is the most commonly used discounted cash flow technique. NPV sums the current value of the investment cost and all future cash flows discounted by the project's cost of capital (i.e., discount rate).* Most spreadsheet software offers the NPV formula as a built-in function.

One-Ti

In the next step, the model calculates the one-time relocation costs. These costs are only incurred in the first year. The model should

- Sum all costs and all benefits in each year
- Calculate the NPV of the total cost savings across each year over n years
- Compare each year's cumulative present value savings to total one-time cost
- Determine if, and year in which, the cumulative net benefit becomes zero or positive (breakeven)

The model should be run as an iterative process to see what happens to the net benefit as model assumptions are changed or new requirements are added.

Recruiting Costs. Recruiting costs are those costs incurred by hiring employees to fill positions in the new location. To calculate recruiting costs for a given scenario, the recruiting cost

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* Businesses typically base a number of investment decisions on U.S. Treasury notes and bond rates. In capital investments, however, the time value of money is also influenced by risk, which can vary. In a business with an average combination of investment risks, standard assumptions of risk are appropriate. Such investments might include a well-balanced portfolio of information technology, financial investments, real estate, and equipment. When a disproportionate share of investments are made in areas of higher-than-average risk—such as information technology—however, then it may be appropriate to use risk-adjusted discount rates for different types of investments.

A QUANTITATIVE APPROACH TO THE SITE SELECTION PROCESS

percentage of an employee is multiplied by the average yearly salary for the job categories. The result is then multiplied by the number of new positions for each job category.

Incentive Pay to Stay. Prior to the date of relocation, employees would be offered a financial incentive to remain with the organization until the final moving date. This incentive will help maintain present levels of productivity, employee morale, and turnover stability in the final months. One approach is to assume a payment similar to severance pay, such as two weeks pay, as an appropriate incentive. To calculate incentive pay costs, the two weeks is multiplied by the average weekly wage for each category of employees not relocating to the new site.

Severance Pay. Severance pay is paid to those employees who choose to terminate employment rather than relocate. The model should differentiate severance pay between exempt and nonexempt staff.

To calculate total severance pay costs, the following equation is used:

$$X = ((A * B) + C) * D$$

where X = total severance pay costs
A = average number of weeks pay
B = average weekly salary of employee
C = outplacement bonus
D = number of terminated positions

Training Costs. Hiring new employees involves lost productivity due to training. For example, it can be assumed that during the on-the-job training period, exempt workers go from 0 to 50 percent productivity in the first month and then to 100 percent productivity over the next nine months. New nonexempt hires go from a 0 percent productivity level to a 75 percent productivity level in the first month of employment and then from 75 to 100 productivity percent from the second month to the seventh month. The time required for a new worker to become fully productive is referred to as the learning curve period.

To calculate total training costs for a labor category, the following equation is used:

$$X = A * B * C * D$$

where X = total training costs
A = percentage loss
B = learning curve
C = average salary per week
D = number of new hires

Dual Operation Costs. During the relocation process, certain departments may move in advance of the official move date while simultaneously operating in their current locations. This overlap period is referred to as *dual operation.* The dual operation requirement results in dual wage and rent costs until operations at the new location are sufficiently phased in. Operation of a new facility prior to complete relocation will also require the supervision by certain key personnel who must travel between sites periodically. The average cost per trip varies by scenario. The dual operation travel costs are computed by simply multiplying the costs per trip by the number of trips expected.

Employee Moving Costs. Moving expenses for relocating employees can be calculated by multiplying the number of moving employees by the industry average allowance of approximately $9,000.* This number can vary based on whether the employee is a homeowner or renter. Similar calculations can be made for office moving expenses.

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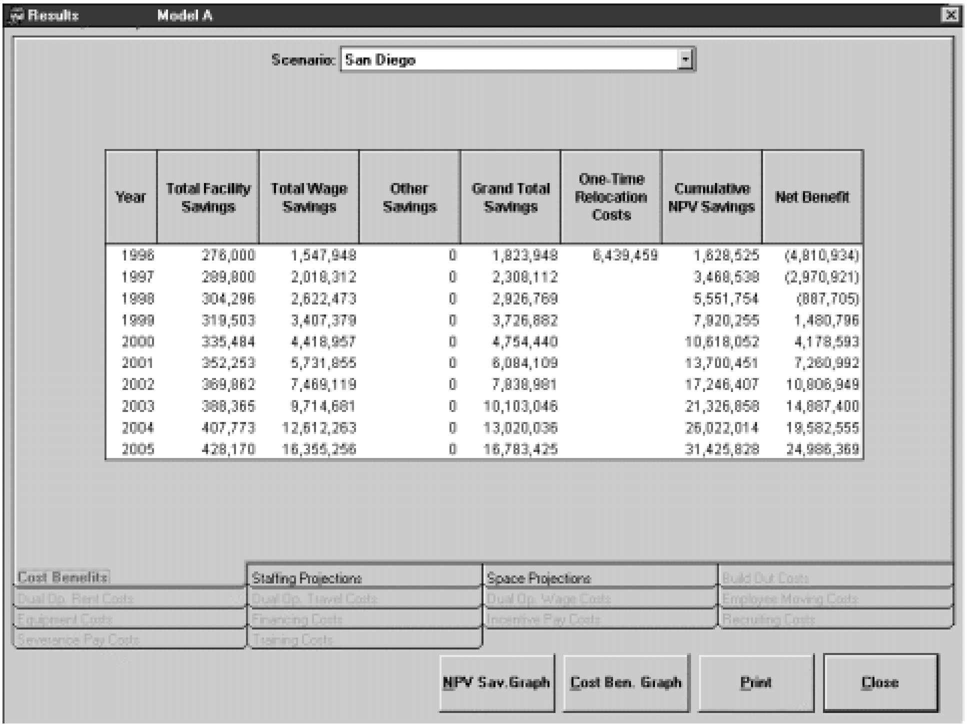
* *Source:* Based on the Runzheimer Plan of Living Cost Standards for domestic and international employee relocation and wage/salary differentials report (www.runzheimer.com).

Financing Costs. Since the one-time relocation costs have an immediate impact on a company's cash position, the model should assume that the entire one-time costs are financed until the break-even year. This presumes that a line of credit can be secured that is paid down from the realized savings. Therefore, an NPV figure of the interest charges for the total one-time costs is added to the final costs.

The sum of all these costs constitutes the one-time relocation costs. Each year's cumulative present value savings for the scenario is then compared to that scenario's total one-time relocation cost. Since the savings have been discounted to a present value for 2001, a useful comparison can be made. By subtracting the one-time costs from the cumulative savings, the net benefit is computed. The year in which the cumulative net benefit becomes zero or positive is the break-even year, that is, the year in which one-time relocation costs are recouped.

Sample Output

Figure 8.1.3 illustrates sample output from the spreadsheet model for a potential relocation site (San Diego). In the example, the one-time costs of $6.4 million are recouped in the fourth year, thereby making 1999 the break-even year. Figure 8.1.4 displays the NPV results in a graphical format. A graph helps decision makers determine the rate of cost savings from the new site. For example, it is often found that a site that may have high one-time costs may actually have a faster return on investment compared to other scenarios.


Results
Model A
Cost Benefits
Staffing Projections
Space Projections
Build Out Costs
Dual Op. Rent Costs
Dual Op. Travel Costs
Dual Op. Wage Costs
Employee Moving Costs
Equipment Costs
Financing Costs
Incentive Pay Costs
Recruiting Costs
Severance Pay Costs
Training Costs
NPV Sav.Graph
Cost Ben. Graph
Print
Close

Scenario: San Diego

Year	Total Facility Savings	Total Wage Savings	Other Savings	Grand Total Savings	One-Time Relocation Costs	Cumulative NPV Savings	Net Benefit
1996	276,000	1,547,948	0	1,823,948	6,439,459	1,628,525	(4,810,934)
1997	289,800	2,018,312	0	2,308,112		3,468,538	(2,970,921)
1998	304,296	2,622,473	0	2,926,769		5,551,754	(887,705)
1999	319,503	3,407,379	0	3,726,882		7,920,255	1,480,796
2000	335,484	4,418,957	0	4,754,440		10,618,052	4,178,593
2001	352,253	5,731,855	0	6,084,109		13,700,451	7,260,992
2002	369,862	7,469,119	0	7,838,981		17,246,407	10,806,949
2003	388,365	9,714,681	0	10,103,046		21,326,858	14,887,400
2004	407,773	12,612,263	0	13,020,036		26,022,014	19,582,555
2005	428,170	16,355,256	0	16,783,425		31,425,828	24,986,369

FIGURE 8.1.3 Sample financial cost-benefit spreadsheet model output.

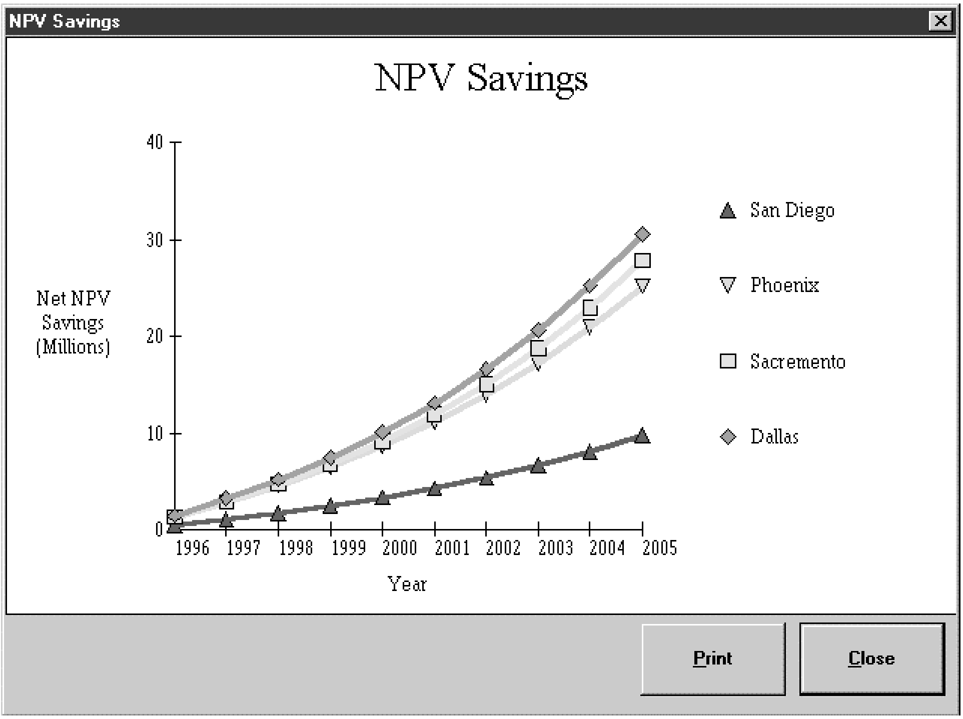

NPV Savings
NPV Savings
Net NPV Savings (Millions)
0
10
20
30
40
1996
1997
1998
1999
2000
2001
2002
2003
2004
2005
Year
▲ San Diego
▽ Phoenix
☐ Sacremento
◇ Dallas
Print
Close

FIGURE 8.1.4 Sample graphical output generated in spreadsheet model.

THE ANALYTIC HIERARCHY PROCESS (AHP) MODEL

The objective of the AHP model* is to first, identify the drivers associated with the site selection; second, organize all of the trade-offs among the competing drivers; and third, help determine appropriate weights to be used in making a final decision.

The AHP is a powerful and comprehensive methodology that provides groups and individuals with the ability to incorporate both qualitative and quantitative factors in the decision-making process. The AHP uses a hierarchical model comprising a goal, criteria, perhaps several levels of subcriteria, and alternatives for each problem or decision. It is a general method for structuring intricate or ill-defined problems and is built around three principles:

1. The principle of constructing hierarchies
2. The principle of establishing priorities
3. The principle of logical consistency

By performing pairwise comparisons on the site selection drivers, it is possible to derive quantitative values (or weights) for the criteria and alternatives. The model will derive priorities based on intangible information from our experience and intuition and tangible information from hard data. By incorporating both subjective judgments and hard data into the decision-making process, we will be much more likely to arrive at a solution that is satisfactory to everyone. AHP will help site selection decision makers

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* The mathematician Thomas L. Saaty at the Wharton School of the University of Pennsylvania developed the AHP model. The software model can be purchased from Expert Choice of Pittsburgh, PA (www.expertchoice.com).

- Incorporate quantitative information as well as knowledge, intuition, and experience
- Consider trade-offs among competing criteria
- Synthesize from the goal to determine the best alternatives
- Communicate the rationale for a decision to others
- Incorporate group judgments

AHP Methodology

1. *Confirm the final list of site selection drivers to be used in the AHP model.* The drivers that could be used in running AHP are endless.* For our example, the final list of drivers consisted of eight factors: cost of operations, labor availability, language ability, educational attainment, climate, cost of living, crime rate, and recreation. Each of these eight drivers is further broken down into subcriteria. For example, the cost of operations criterion is broken down into four subdrivers: very expensive, expensive, average, and low.

2. *Based on conversations with site selection managers, determine the importance of the site selection drivers with respect to each other.* After all the drivers and subdrivers have been input into the AHP model, comparison matrices are generated. The final ranking of drivers is based on how these matrices were completed. First, the AHP model asks the decision maker to compare the relative preference between each pair of subdrivers. For example, for cost of operations, there are six preferences: very expensive (VE) versus expensive (E); (VE) versus average (A); VE versus low (L); E versus A; E versus L; and A versus L. Each preference is important not only to itself but also to the overall matrix that is developed.

After the initial subcriteria matrices are completed, a final matrix, which compares all of the high-level site selection drivers, is filled out. This matrix consists of a pair-to-pair comparison of each driver (see Fig. 8.1.5). The simple matrix is used to record management responses as to the importance of one factor versus another. Given the criteria identified previously, a comparison can be made between each and every factor using a nine-point rating scale. For example, the element in the first column and third row (A versus C) should read, "The financial cost-benefit is *how much more important* than the telecommunications infrastructure?" Only one-half of the matrix is filled in. The even numbers can be used in the case of a tie between rating choices (see Table 8.1.1).

3. *Input the data into the AHP model and generate final weights.* The final matrix to be generated using the AHP consists of the potential locations being considered, while the top row lists the drivers that are being used to determine ranks. The first step is to enter how each location rates for each driver.† After selecting the appropriate subdrivers under each driver for each potential location, a total weighted rank is generated. For example, decision makers should be consistent on judging whether the financial cost-benefit for a particular location is deemed to be very expensive versus moderate (see Tables 8.1.2 and 8.1.3). The final ranking is determined by inputting these evaluations into the AHP model to determine the top locations that best fit the criteria. This is expected to be an iterative process in that drivers and subdrivers can be reevaluated until the results are satisfactory.

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* See Conway McKinley reference for additional criteria.

† Objective evaluations should be made using recent trade publications, almanacs, or the U.S. Statistical Abstract. Subjective judgments from several decision makers should also be used.

Site Selection Drivers

A. Financial Cost-Benefit
B. Labor Availability/Cost/Quality
C. Telecommunications Infrastructure
D. Banking Infrastructure
E. Postal Infrastructure
F. Cost of Living
G. Cultural/leisure Activities

Comparison Rating Scale

1) Indifferent
2)
3) Slightly More Important
4)
5) Moderately More Important
6)
7) Strongly More Important
8)
9) Absolutely More Important

	A	B	C	D	E	F	G
A	1						
B		1					
C			1				
D				1			
E					1		
F						1	
G							1

FIGURE 8.1.5 Evaluation matrix survey.

FUTURE TRENDS IN SITE SELECTION MODELING

- B2B trade exchanges
- Enterprise resource planning software
- Data mining and decision support
- Distribution strategies in the age of the Internet
- E-commerce sales taxation
- Telecommuting and alternative workplace strategies

TABLE 8.1.1 Sample AHP Pairwise Comparison Matrix*

Column A		Column B
Financial cost-benefit	3	Labor availability
Financial cost-benefit	5	Telecommunications
Financial cost-benefit	6	Postal capabilities
Financial cost-benefit	9	Recreation
Financial cost-benefit	5	Cost of living
Financial cost-benefit	7	Banking infrastructure
Financial cost-benefit	9	Recreation
Labor availability	4	Telecommunications
Labor availability	4	Postal capabilities
Labor availability	9	Recreation
Labor availability	4	Cost of living
Labor availability	4	Banking infrastructure
Labor availability	9	Recreation
Telecommunications	2	Postal capabilities
Telecommunications	8	Recreation
Telecommunications	2	Cost of living
Telecommunications	3	Banking infrastructure
Telecommunications	7	Recreation
Postal capabilities	8	Recreation
Postal capabilities	3	Cost of living
Postal capabilities	3	Banking infrastructure
Postal capabilities	8	Recreation
Cost of living	3	Recreation
Banking infrastructure	6	Recreation
Recreation	1	Recreation
Banking infrastructure	2	Cost of living
Cost of living	2	Recreation
Banking infrastructure	6	Recreation

* The table should be read as “Column A is (rating) compared to Column B.”

Rating scale for comparison
1 = Indifferent
2 =
3 = Slightly more important
4 =
5 = Moderately more important
6 =
7 = Strongly more important
8 =
9 = Absolutely more important

TABLE 8.1.2 Final Weights Generated by the AHP

Site selection driver	AHP generated weight
A. Financial cost-benefit	0.386
B. Labor availability/cost/quality	0.236
C. Telecommunications infrastructure	0.120
D. Banking infrastructure	0.107
E. Postal infrastructure	0.019
F. Cost of living	0.046
G. Recreation/cultural activities	0.020

TABLE 8.1.3 Sample Final Output of Location Rankings Using AHP

Rank	Location	Final weight	Financial cost-benefit	Labor availability	Telecom infrastructure	Banking infrastructure	Postal infrastructure	Cost of living	Recreation/ cultural activities
1	Site A	0.940	Low	High	Good	Good	Poor	Inexpensive	Great
2	Site B	0.908	Low	Moderate	Good	Good	Poor	Inexpensive	Poor
3	Site C	0.792	Low	High	Average	Poor	Good	Inexpensive	Great
4	Site D	0.778	Low	Moderate	Good	Good	Poor	Expensive	Poor
5	Site E	0.752	Low	Moderate	Average	Good	Good	Inexpensive	Average
6	Site F	0.671	Average	High	Average	Good	Average	Inexpensive	Good
7	Site G	0.626	Average	High	Average	Good	Good	Very expensive	Great
8	Site H	0.600	Average	High	Poor	Good	Average	Very expensive	Poor
9	Site I	0.591	Expensive	Moderate	Good	Good	Poor	Very expensive	Great
10	Site J	0.590	Low	Moderate	Poor	Poor	Good	Inexpensive	Good

A QUANTITATIVE APPROACH TO THE SITE SELECTION PROCESS

APPENDIX: LABOR AVAILABILITY

The availability of labor can be assessed by comparing various indicators among several selected metropolitan locations to obtain a sense of the relative strength of each measure by comparative analysis. The relative importance of each factor depends on the strategic goals of company management and their judgment of the factors. The current location is treated as the benchmark.

Some of the factors at a macro level favorable to labor availability include

- Large population or labor force in a given area
- Strong projected growth in the population or labor force
- Significant representation of related jobs and industry
- Strong projected growth in related jobs
- Surplus labor market
- Strong presence of educational institutions to support high-tech industry
- Good transportation infrastructure, which creates a geographically defined labor market larger than what it would be otherwise

SAMPLE METHODOLOGY

There are 266 metropolitan statistical areas (MSAs) in the United States and Canada. The first step in narrowing the list of potential MSAs down to 10 is to rank all 266 areas in order of unemployment rate.* The MSA with the highest unemployment rate is given a ranking of 1, the next highest, 2, and so on (see Table A.1).

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* Unemployment rates from the U.S. Bureau of Labor Statistics (http://stats.bls.gov/) can be used.

TABLE A.1 MSA Rank by Unemployment Rate

Rank	MSA	Unemployment rate (%)
1	Brownsville, Texas	15.1
2	Modesto, California	13.1
3	El Paso, Texas	12.4
4	Fresno, California	12.2
5	Bakersfield, California	11.6
6	Montreal, Canada	11.5
7	Greenville, Mississippi	10.6
7	Stockton, California	10.6
9	Beaumont, Texas	10.0
9	Toronto, Canada	10.0
11	Chico, California	9.8
50	Benchmark	6.4

The second step is to rank all 266 areas in order of a weighted salary for the positions expected in the new location. For example, Table A1.2 shows the annual median base salary for each of four positions: accountant, accounting clerk, administrative assistant, and bookkeeper.*

The weighted salary is calculated by separating the positions into two categories: exempt and nonexempt. The accountant salary is used in this example to represent the exempt salary. The other three positions can be averaged to represent a nonexempt salary (see Tables A1.3 and A1.4).

If it is estimated that 75 percent of the labor cost at the new location will be for nonexempt employees and 25 percent for the exempt employees, a total weighted salary can be computed by taking each MSA and applying the following formula:

$$(.75 * A) + (.25 * B)$$

where A = MSA nonexempt average salary
B = MSA exempt salary

FINAL RANKINGS

Combining the two sets of MSA rankings into an overall ranking provides a list of the top 10 MSAs from which to begin the detailed cost analysis (see Table A1.5). The initial sites identified in this example meet the labor availability objective. To further narrow the list, other labor availability criteria such as measuring the number of associate degrees awarded and the transportation infrastructure available to the geographic labor market can be added to the decision matrix.

To make the wage rankings more reflective of the marginal differences, the range of weighted wages should be spread over a normal statistical distribution and divided into 10 equal percentile groups. For example, of the 200 MSAs, the 20 MSAs with the lowest wages made up the first 10th percentile group and were given a rank of 1. The next 20 MSAs with the

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* Salary data obtained from the U.S. Bureau of Labor Statistics (http://stats.bls.gov/).

TABLE A1.2 Annual Median Base Salary by MSA

MSA	Unemployment rate (%)	Accountant	Account clerk	Administrative assistant	Bookkeeper
Abilene, Texas	5.2	$35,947	$18,162	$27,767	$21,309
Akron, Ohio	4.1	$39,278	$20,131	$30,557	$23,910
Albany, Georgia	6.7	$35,844	$18,178	$27,896	$21,425
Albany, New York	4.9	$42,075	$22,221	$33,605	$26,509
Albuquerque, New Mexico	5.5	$36,334	$18,134	$27,638	$21,631
Alexandria, Louisiana	7.9	$37,983	$18,934	$29,152	$22,417
Allentown, Pennsylvania	5.4	$38,407	$19,731	$29,863	$23,415
Altoona, Pennsylvania	5.6	$37,393	$18,893	$28,856	$22,398
Amarillo, Texas	4.0	$35,008	$17,574	$26,849	$20,312
• • •	• • •	• • •	• • •	• • •	• • •

TABLE A1.3 MSA Rank by Accountant Salary

Rank	MSA	Accountant salary
1	Edmonton, Canada	$29,730
2	Montreal, Canada	$32,107
3	Augusta, Georgia	$32,896
4	Las Cruces, New Mexico	$33,429
5	Rapid City, South Dakota	$33,701
6	Brownsville, Texas	$33,753
7	Pierre, South Dakota	$33,943
8	Daytona Beach, Florida	$34,036
9	Vancouver, Canada	$34,144
10	Tallahassee, Florida	$34,306
227	Benchmark	$41,005

TABLE A1.4 Rank of MSA by Average Nonexempt Salary

Rank	MSA	Average nonexempt salary
1	Edmonton, Canada	$19,128
2	Las Cruces, New Mexico	$19,694
3	Rapid City, South Dakota	$20,549
4	Pocatello, Idaho	$20,573
4	Twin Falls, Idaho	$20,573
6	Boise, Idaho	$20,693
7	Idaho Falls, Idaho	$20,742
7	Tallahassee, Florida	$20,742
9	Daytona Beach, Florida	$20,769
10	Brownsville, Texas	$20,802
216	Benchmark	$25,924

TABLE A1.5 MSA Rank by Unemployment and by Salary

Rank	MSA by unemployment	Rank	MSA by salary
1	Brownsville, Texas	1	Las Cruces, New Mexico
2	Modesto, California	2	Edmonton, Canada
3	El Paso, Texas	3	Rapid City, South Dakota
4	Fresno, California	4	Brownsville, Texas
5	Bakersfield, California	5	Pocatello, Idaho
6	Montreal, Canada	6	Twin Falls, Idaho
7	Greenville, Mississippi	7	Daytona Beach, Florida
7	Stockton, California	8	Boise, Idaho
9	Beaumont, Texas	9	Tallahassee, Florida
9	Toronto, Canada	10	Pierre, South Dakota
11	Chico, California	11	Idaho Falls, Idaho
50	Benchmark	221	Benchmark

A QUANTITATIVE APPROACH TO THE SITE SELECTION PROCESS

lowest wages are grouped into the second 10th percentile and given a rank of 2, and so forth. By grouping and ranking the MSAs in this manner, it ensures that 2 MSAs with wages within a few dollars of each other do not have a large difference in their ranking.

To make the unemployment rate rankings compatible with the wage rankings, the same percentile grouping methodology can be used. Again, the objective here is to reduce the variation in unemployment rates and thus prevent 2 MSAs with unemployment rates within a few percentage points of each other from having very different rankings.

Since labor cost is treated as more important than unemployment rate, the salary rankings are more heavily weighted. By applying the following formula, a final ranking can be computed (see Table A1.6).

TABLE A1.6 Final Ranking of Metropolitan Statistical Areas

Ranking	Metropolitan statistical area	Weighted value
1	Brownsville, Texas	1.0
1	Las Cruces, New Mexico	1.0
1	Edmonton, Canada	1.0
4	Montreal, Canada	1.2
5	Florence, Alabama	1.4
6	Waco, Texas	1.6
7	Longview, Texas	1.8
7	El Paso, Texas	1.8
7	Florence, South Carolina	1.8
10	Santa Fe, New Mexico	2.0

$$\text{Final Rank} = (.6 * \text{A}) + (.4 * \text{B})$$

A = the rank of each MSA by salary
B = the rank of each MSA by unemployment

I wish to thank Dr. George Kettner of Economic Systems, Inc., for helping pioneer the effort in site selection cost modeling, and Thomas Saaty of Expert Choice for pioneering the effort in the AHP for decision making.

FURTHER READING

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BIOGRAPHY

Raj Patel has conducted numerous site selection studies working as a management consultant to Fortune 1000 firms. He has over eight years experience in the areas of real estate economic analysis, business process improvement, and information technology for both the public and private sector. He has developed a proprietary site selection software model that enables firms to compute and analyze any number of relocation scenarios. Currently, Patel is the chief information officer of Forest City Ratner Companies, an owner and developer of commercial and retail real estate in New York City (www.fcrc.com). Previously, Patel was a manager in the Management Consulting Practice of Ernst & Young LLP, specializing in information systems for the real estate industry. He has an M.B.A. from Georgetown University and a B.A. in economics from the University of California at Berkeley.

CHAPTER 8.2

FACILITIES LAYOUT AND DESIGN

William Wrennall
The Leawood Group, Ltd.
Leawood, Kansas

This chapter takes the reader through a process from an organization's business strategy to a facility layout and design that supports the strategic intent. The strategic facilities planning process (SFP) goes beyond the systematic approach. SFP incorporates the concepts of focus, JIT, pull systems, cellular, and lean operations. This demands a change of emphasis for the facility planner from block layouts to detailed or populated layouts. The re-layout process becomes a macro productivity improvement opportunity.

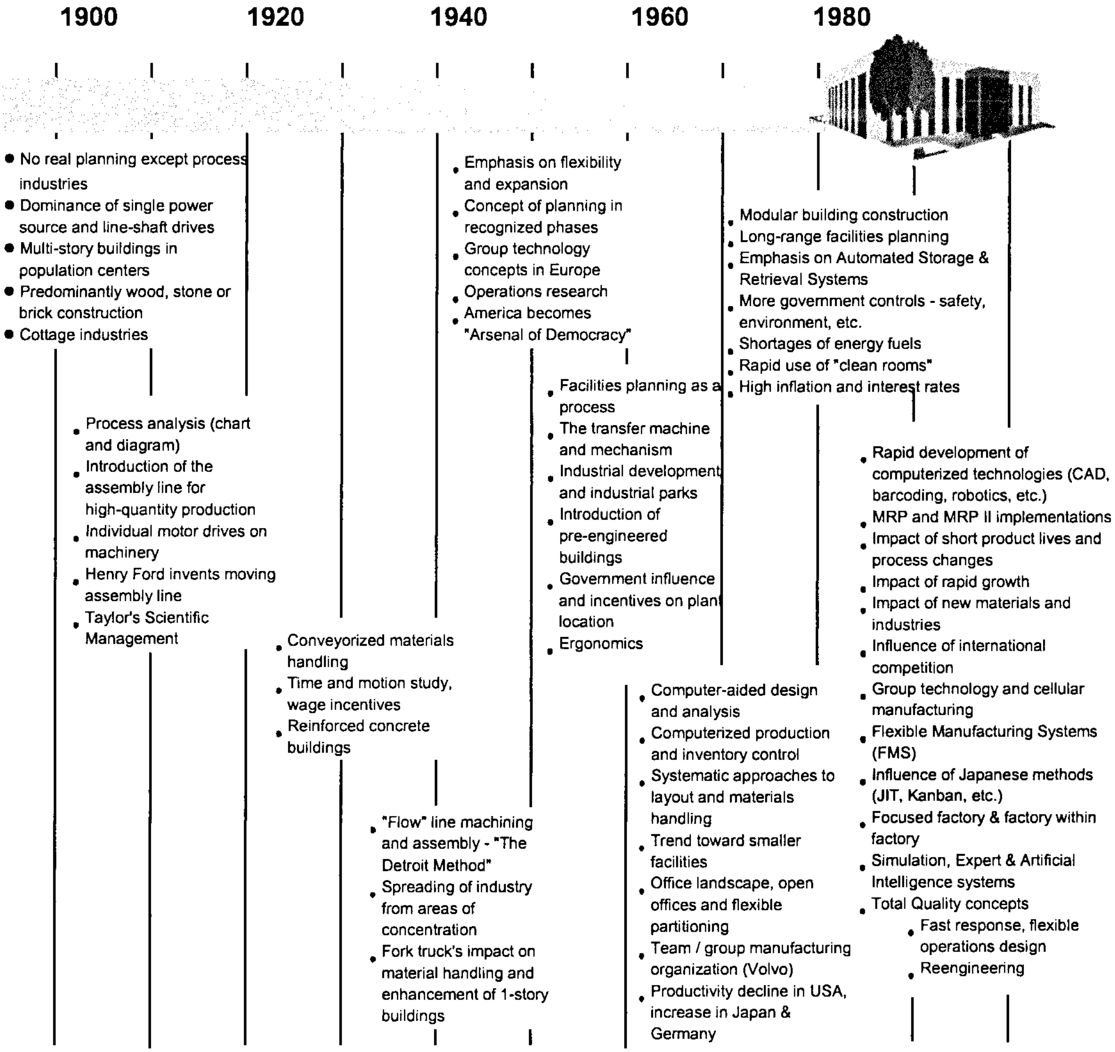
INTRODUCTION

Facilities are the physical representation of the capacity of an operation. They promote or constrain the efficiency of operations. Facility layout is the planning, designing, and physical arrangement of processing and support areas within a facility; the goal is to create a design that supports company and operating strategies. From the Latin *facilis,* meaning *easy,* a facility should free operations within it from difficulties or obstacles. A good layout optimizes the use of resources while satisfying other criteria such as quality, control, image, and many other factors. Because of these many factors, facilities layout is very complex. The evolution of facility structures, processes, materials handling, and other factors that influenced design are shown in Fig. 8.2.1.

This chapter guides the planner and clarifies the layout process. The procedure also shows how to design layouts that support lean operations (*lean* in that they omit "fat" but retain value). The model is given in Fig. 8.2.2.

The principles and techniques described in this chapter are applicable to the layout and design of manufacturing plants, warehouses, distribution centers, offices, and laboratories. However, the approaches to manufacturing in particular have made major advances in recent years. New strategies have a significant impact on space requirements and activities focus. These changes demand compatible shifts in the design of their layouts. This chapter gives examples of recent applications resulting from new thinking as it affects facilities design across the spectrum of operations including

- Data collection and analysis
- Major steps in creating an efficient facility layout
- Quick but accurate development of space requirements



- No real planning except process industries
- Dominance of single power source and line-shaft drives
- Multi-story buildings in population centers
- Predominantly wood, stone or brick construction
- Cottage industries

- Process analysis (chart and diagram)
- Introduction of the assembly line for high-quantity production
- Individual motor drives on machinery
- Henry Ford invents moving assembly line
- Taylor's Scientific Management

- Conveyorized materials handling
- Time and motion study, wage incentives
- Reinforced concrete buildings

- "Flow" line machining and assembly - "The Detroit Method"
- Spreading of industry from areas of concentration
- Fork truck's impact on material handling and enhancement of 1-story buildings

- Emphasis on flexibility and expansion
- Concept of planning in recognized phases
- Group technology concepts in Europe
- Operations research
- America becomes "Arsenal of Democracy"

- Facilities planning as a process
- The transfer machine and mechanism
- Industrial development and industrial parks
- Introduction of pre-engineered buildings
- Government influence and incentives on plant location
- Ergonomics

- Computer-aided design and analysis
- Computerized production and inventory control
- Systematic approaches to layout and materials handling
- Trend toward smaller facilities
- Office landscape, open offices and flexible partitioning
- Team / group manufacturing organization (Volvo)
- Productivity decline in USA, increase in Japan & Germany

- Modular building construction
- Long-range facilities planning
- Emphasis on Automated Storage & Retrieval Systems
- More government controls - safety, environment, etc.
- Shortages of energy fuels
- Rapid use of "clean rooms"
- High inflation and interest rates

- Rapid development of computerized technologies (CAD, barcoding, robotics, etc.)
- MRP and MRP II implementations
- Impact of short product lives and process changes
- Impact of rapid growth
- Impact of new materials and industries
- Influence of international competition
- Group technology and cellular manufacturing
- Flexible Manufacturing Systems (FMS)
- Influence of Japanese methods (JIT, Kanban, etc.)
- Focused factory & factory within factory
- Simulation, Expert & Artificial Intelligence systems
- Total Quality concepts

- Fast response, flexible operations design
- Reengineering

FIGURE 8.2.1 Facility planning chronology. (*Courtesy of The Leawood Group 91778 Rev.*)

- Relationships between space planning units
- Selecting the best layout

In the early 1980s the first news began to filter out of Japan about the Toyota manufacturing system called just-in-time (JIT). Since then JIT has matured. It is one of several manufacturing strategies emphasizing reduction of inventory and integration of people and technology. Other names for these strategies, or developments from them, are world-class manufacturing (WCM) and lean operations. Such strategies typically have the following elements:

- Customer focus
- Real-time data collection and processing

FACILITIES LAYOUT AND DESIGN

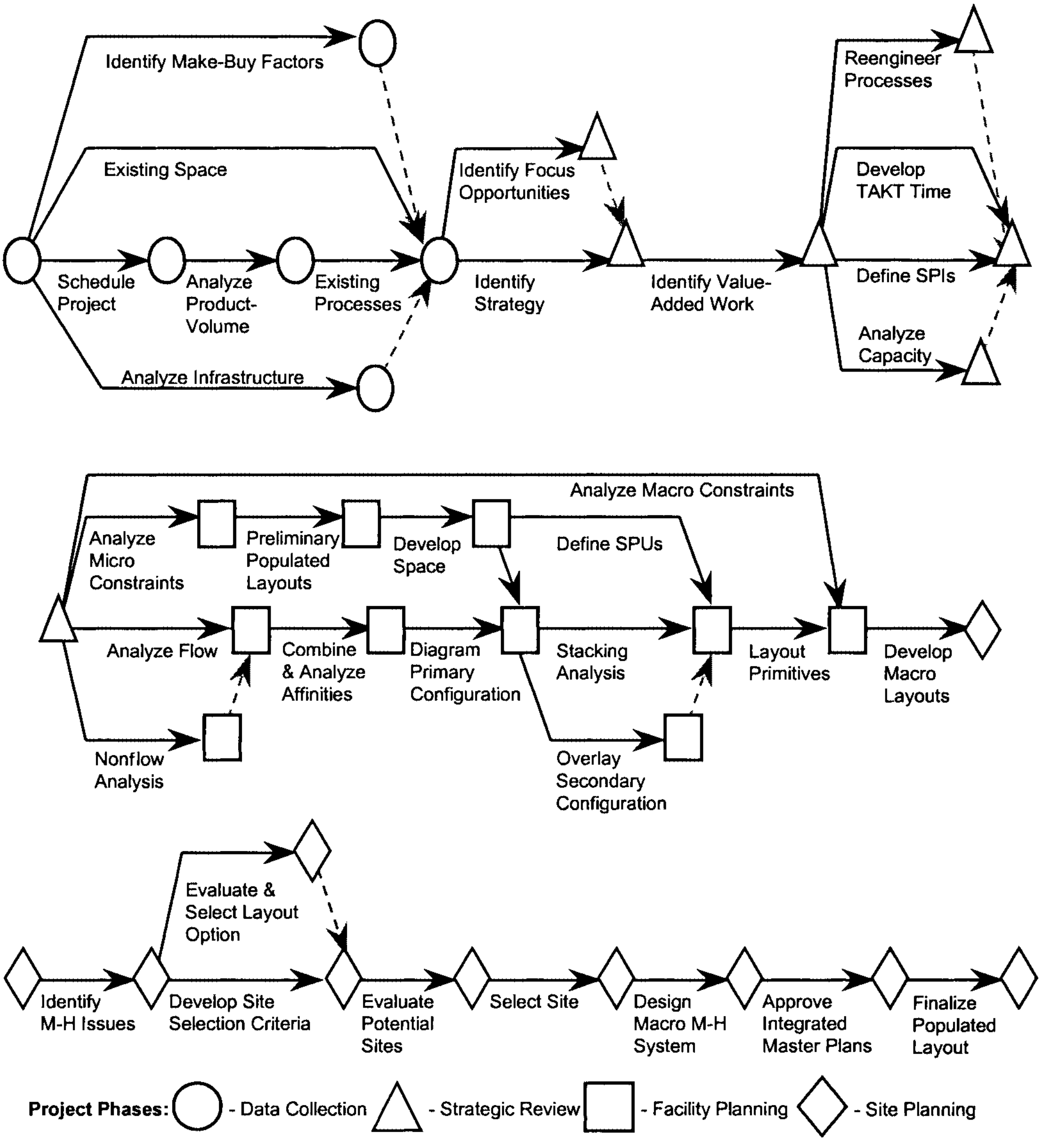

Identify Make-Buy Factors
Existing Space
Schedule Project
Analyze Product-Volume
Existing Processes
Analyze Infrastructure
Identify Focus Opportunities
Identify Strategy
Identify Value-Added Work
Reengineer Processes
Develop TAKT Time
Define SPIs
Analyze Capacity
Analyze Macro Constraints
Analyze Micro Constraints
Preliminary Populated Layouts
Develop Space
Define SPUs
Analyze Flow
Combine & Analyze Affinities
Diagram Primary Configuration
Stacking Analysis
Layout Primitives
Develop Macro Layouts
Nonflow Analysis
Overlay Secondary Configuration
Evaluate & Select Layout Option
Identify M-H Issues
Develop Site Selection Criteria
Evaluate Potential Sites
Select Site
Design Macro M-H System
Approve Integrated Master Plans
Finalize Populated Layout
Project Phases:
- Data Collection
- Strategic Review
- Facility Planning
- Site Planning

FIGURE 8.2.2 Lean operations generic project model.

- Rapid setup
- JIT manufacturing system
- JIT accounting
- Focused factories
- Supplier networks
- Capacity reserve

- Total quality
- Group technology
- Cellular operations
- The team approach
- Process leaning

A synergy is at work among these elements of strategic facility layout and manufacturing strategy. Strategy directly affects layout; layout design, in turn, profoundly affects the success of the strategy.

MANUFACTURING STRATEGY

Manufacturing strategy is the underlying philosophy of a manufacturing system. It manifests itself as the pattern of management decisions over time, the range and grouping of products, the types of support systems used, the selection and arrangement of equipment, and employees and their attitudes. A manufacturing strategy should be explicit, consistent, and well thought out. More often it is implicit, inconsistent, and haphazard. A manufacturing strategy guide sheet is given as Appendix A to this chapter. Regardless of management's strategic sophistication, the designer of a facilities layout should know the vision or strategy the firm will follow. The layout can then reflect and support that strategy.

OVERVIEW OF THE LAYOUT LIFE CYCLE

The layout process proceeds from the general to the particular: from a general framework, or structure, to the location of each piece of equipment in each workplace. This procedure provides ease in arriving at a sound and logical arrangement of space planning units, or blocks of space. The layout must first be sound in principle; then the detail is increased step-by-step within the sound layout that has been approved, until the layout is complete. A detailed generic project plan is described in the next major section of this chapter.

In our structured layout planning approach we recommend phasing the facilities project. Figure 8.2.3 illustrates a five-phase plan. The five phases lead into an organized method for

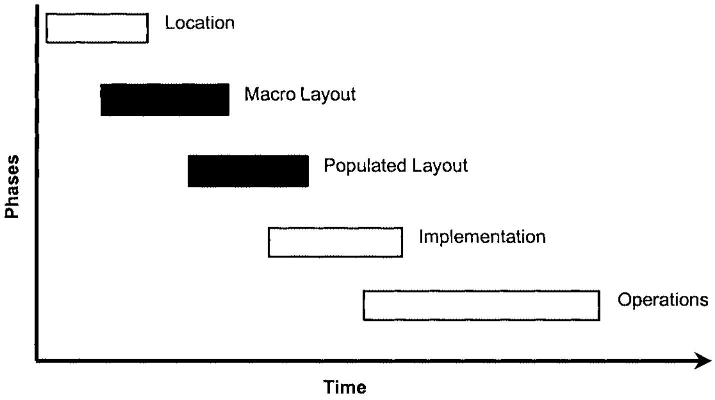


FIGURE 8.2.3 Layout project life cycle.

developing a layout. In the phase diagram time is represented horizontally. The times shown for each phase are for the purpose of demonstration and do not represent any particular project. Phase overlap shows that phases can begin before the completion of the prior phase, but cannot be completed before the completion of the previous phase. The greater the phase overlap the shorter the time for completion of the project. This is desirable to improve productivity of layout planning.

Phase 1—Location is where the project is defined and the layout planners are oriented to the project. At this time the following questions must be answered:

- Which site is to be considered?
- What building is to be used?
- What is the scope of the project?
- What is the schedule?
- What are the tasks and deliverables?
- Who will staff the design project?

Phase 2—Macro layout is the main planning phase where business plans, strategy, focus, and so on, are integrated to develop macro layouts, sometimes called block layouts. These layouts consist of the arrangement of blocks of space, called space planning units (SPUs), in a regular shape. In the macro layout only the SPU outlines are given. These outlines should not be interpreted as walls. They may change after refining in phase 3 and structural building requirements are known. The enveloped shape for the layout may be that of an existing building, floor, or area; it may be conceptual and free from structural or size constraints; it may be the basis for a future building design.

Phase 3—Populated layout is for the populated or detail layout. The term *populated layout* was first suggested by Leo Vogel of the U.S. Postal Service (USPS). Although due deference is given to the macro layout design, where the major areas are to be located in relation to each other, populating the blocks (arranging the equipment and support services) is not a trivial matter. Populated layouts are operational, block (macro) layouts are not. The proof of a layout is in its population, or the detail. Contrary to conventional assumptions, populated SPUs are often prerequisites as well as successors to determining macro layouts and optimizing such elements as new building column spacing. Typical examples are groups of large mail-sorting machines, large plating installations, or paint applications with drying ovens that require detailed equipment layouts to determine block (or macro), space, and shape requirements. The blocks, or SPUs, from the macro layout are now given operational meaning. Equipment, furniture, utilities, building features, aisles, and material locations are determined.

Phase 4—Implementation is where the physical arrangement occurs. The layout plans are extended into an implementation plan, which is then executed. The result is the physical layout.

Phase 5—Operations start-up occurs in this phase when the layout design is tested and the facility is transformed into an operating unit. In Fig. 8.2.4, planning costs and benefits are added to the layout life cycle phase diagrams. The layout life cycle cost and impact curve show the cost and the strategic impact at each phase. In the early phases cost is low but strategic impact is high. These early phases thus have an important long-term effect on operations and largely decide profitability. *The early phases are not the place to economize.* In the later phases—(3) populated, micro, or detailed layout, (4) implementation, and (5) operation—costs peak. With the advent of lean operations and product focused cells, focus refinements now extend strategic impact. The relatively inexpensive strategic and macro planning has by far the greatest impact on future company operating/business costs. Subsequent expenditures on phases 3, 4, and 5 (including construction and equipment costs) have relatively minor impact on future operations.

Thorough layout planning leads to workable layouts and efficient operations. Retrofits or afterthought corrections are also minimized.

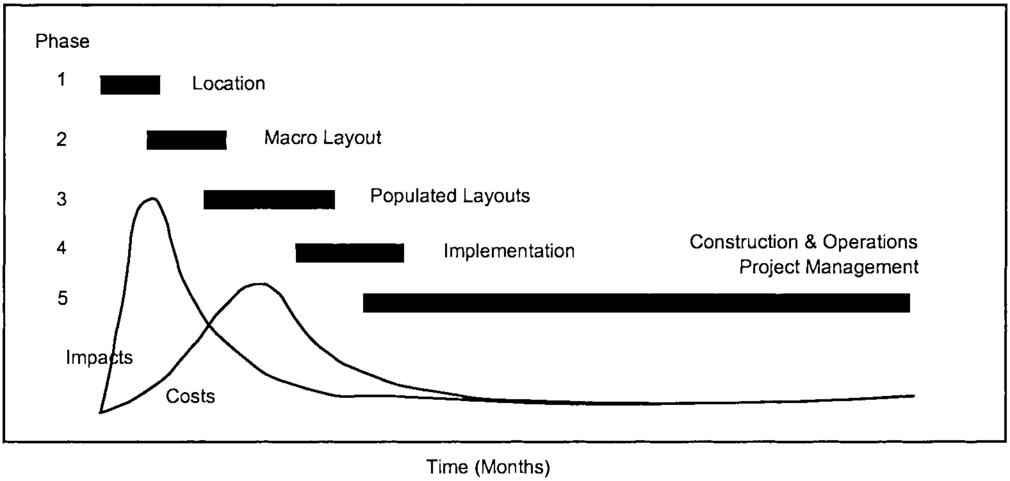


FIGURE 8.2.4 Layout planning phases with costs and impacts.

THE GENERIC DETAILED PROJECT PLAN

Facilities layout projects transform a manufacturing strategy into a physical capability. The project structure shows the following steps, which make up the generic project plan:

- Information acquisition
- Strategic analysis
- The layout process
- Integration
- Populating the layout
- Implementation

For managing a layout project, it is convenient to extend these steps into a network of activities and tasks. The network is illustrated as a lean operations generic project plan given earlier in Fig. 8.2.2. The tasks and their outputs, or deliverables, as organized can be classified as information acquisition, strategic analysis, and site and facility planning, which lead to integration and implementation. The generic project plan provides a set of tasks and sequences that guide a layout project, large or small, simple or complex. To arrive at a layout the designer must accomplish each task in some manner. The formality of analysis, the specific techniques, rigor, creative insight, expended resources, and required time vary from project to project. The project plan builds on experience with techniques developed by Muther [1] and others. The first task is to scope and schedule the project. For a major new facility this may require a detailed schedule using computer-aided project management. For a small plant or department the scope and schedule may exist only in the mind of the designer, but must be communicated to internal customers.

INFORMATION ACQUISITION

In this part of the project the designer or project team, see Tuttle [2], embarks on the following series of tasks to gather information, organize it, and develop preliminary conclusions:

- Document the existing processes.
- Catalog current or needed use of space.
- Identify present and future infrastructure requirements.
- Determine outsourcing policies.

When these tasks are completed the project team has a thorough understanding of the current and past situation. It is then in a position to develop a strategic base for the layout, looking long-term with today's best logic and knowledge of possible scenarios.

STRATEGIC ANALYSIS

One of the elements of a lean operation strategy is focused manufacturing, which limits activity in an organization to a manageable and consistent set of tasks that directly support the firm's marketing strategy. Such a focus concentrates expertise and promotes superior performance, although in a narrow range. It is not uncommon to see inappropriate manufacturing focus built into plant layouts, typically where a functional layout is producing high or medium (batched) volume products. For example, a manufacturer of computers with five basic models, assembling 3 to 10 of each per day, may use a large functional assembly area. A preferred layout for a new plant could be a small assembly line for each basic model, or product-focused assembly cells. Prototypes and replacement parts manufacture could still require functional areas. Most manufacturing (and other organizations as well) display a strong bias for the functional mode. The reasons for this bias are unclear, but there are several possibilities:

- Functional layouts are often easier to design.
- Accounting systems do not penalize the high inventory required by functional layouts.
- Financial policies emphasize high equipment utilization and, in theory, favor functional layouts.
- Engineers favor high-tech, costly, and large-scale equipment that demands high utilization. This also favors a functional layout.

Manufacturers misuse the functional mode most often. However, any mode has the potential for misapplication. In one situation, a Detroit-style assembly line builds massive off-road vehicles at 1 to 2 per day. The results are poor.

Focus Analysis

The layout designer can achieve an optimum degree and mix of manufacturing focus by using the algorithm given in Fig. 8.2.5. The product-focused modes, especially line and continuous, offer many advantages in quality, low inventory, and efficiency. The process-focused functional mode is most frequently misapplied. For these reasons, the algorithm starts with a pure product focus and line production. It then backs away through the JIT, cellular, and functional modes toward an acceptable alternative.

Step 1 starts with an operation process chart for each distinct product. Any industrial engineering handbook or text shows the conventions for constructing these charts. The charts are lined up side by side as shown in Fig. 8.2.6. Each operation on a product is a product operation (PO). In the typical situation a single PO requires too little time and equipment for a dedicated workstation or department. The layout designer must somehow group various POs. One method groups all POs that require the same equipment or type of process. Envelopes 1 and 2 on Fig. 8.2.6 illustrate this. Such grouping provides a pure process focus. Alternatively, a designer might group all operations required by a single product. Locating these in a single

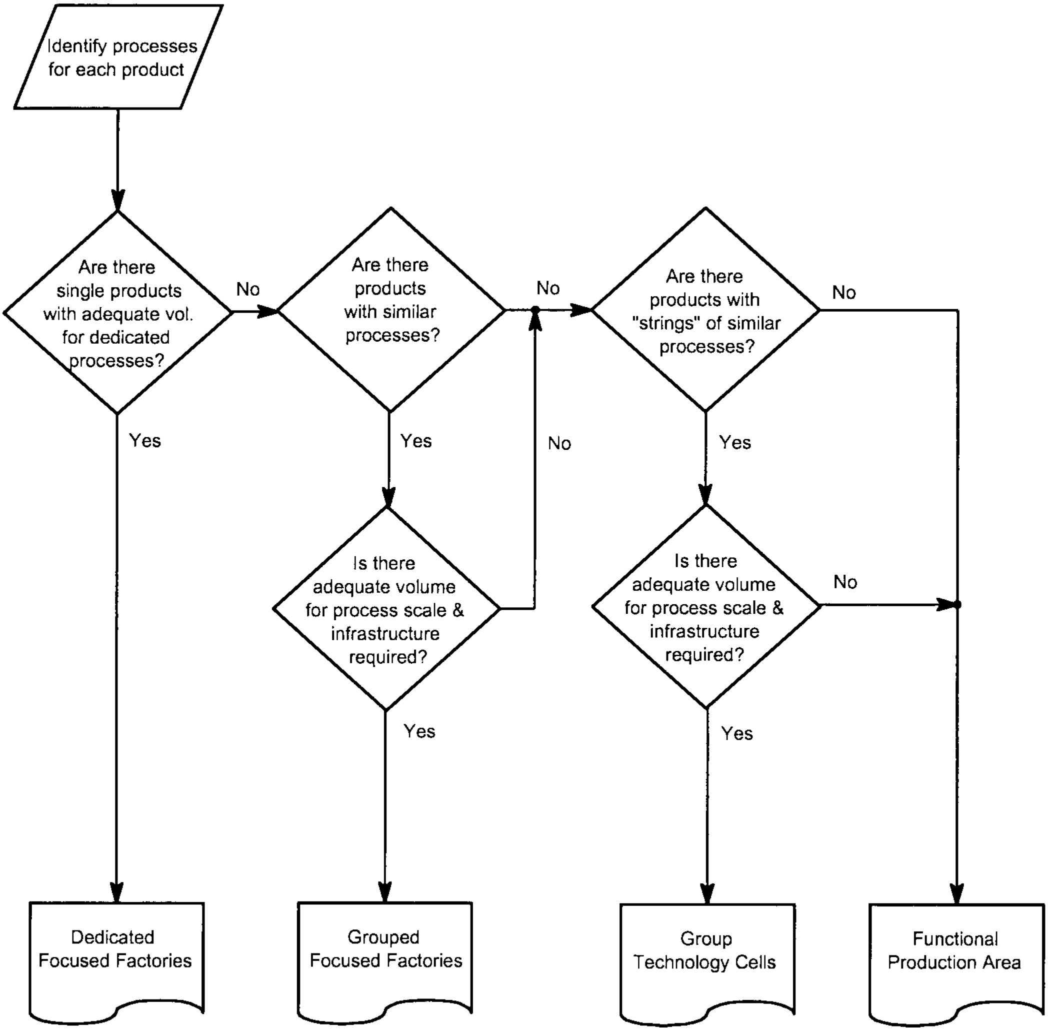

Identify processes for each product
Are there single products with adequate vol. for dedicated processes?
No
Yes
Are there products with similar processes?
No
Yes
Is there adequate volume for process scale & infrastructure required?
No
Yes
Are there products with "strings" of similar processes?
No
Yes
Is there adequate volume for process scale & infrastructure required?
No
Yes
Dedicated Focused Factories
Grouped Focused Factories
Group Technology Cells
Functional Production Area

FIGURE 8.2.5 Manufacturing focus algorithm.

product department or workstation gives a pure product focus. This is illustrated in envelope 3. In step 2, the designer examines each product for a trial product-focused grouping. There are, we believe, only two valid reasons for rejecting a pure product focus:

1. The available processes have large capacities that cannot economically produce a single product. For example, a small turned pin requires only 0.25 machine-hours per week for the expected product volume.
2. Some element of the infrastructure is large scale, which cannot effectively serve a single low-volume product. For example, a highly skilled electronic technician calibrates a circuit board, but production of the single product requires his or her skills only about two hours per week.

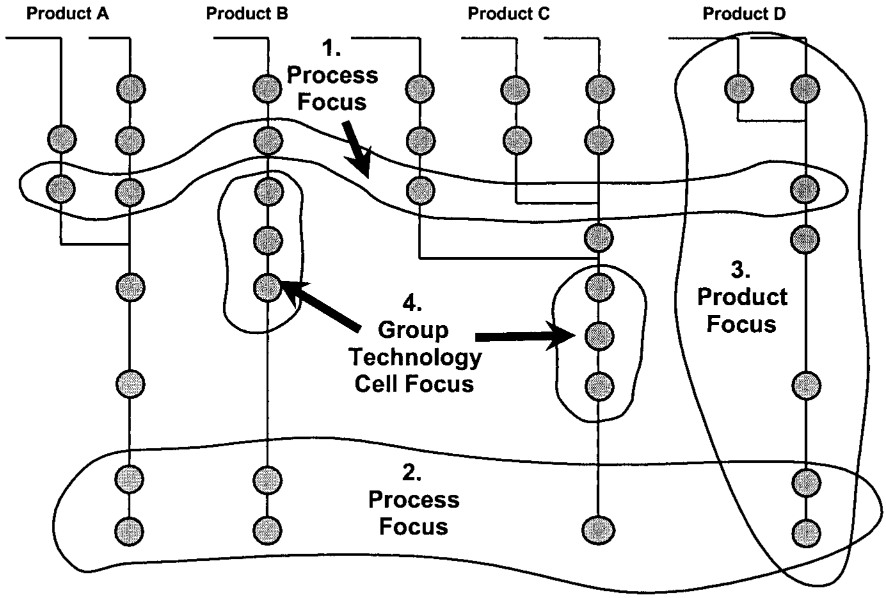


FIGURE 8.2.6 Optimizing manufacturing focus.

If neither of these conditions applies to the trial product, it should have its own manufacturing area and possibly its own plant within a plant (PWP). These products are then removed from further consideration. In step 3 the designer examines each remaining product, identifying subsets of the manufacturing processes (strings) that are common to two or more products. When such a string occurs, the designer tests it for adequate volume vis-à-vis process and infrastructure scale. If the strings pass the test, they become group technology cells as in envelope 4.

The group technology (GT) concept originally embraced families of parts manufactured in machine groupings called GT cells. However, GT cells are not necessarily restricted to manufacturing cells for machined parts; they can be natural groupings of castings such as lamp bases for finishing, common components for assembly, or for operations using similar processes. Step 4 collects all remaining operations into functional areas. The identified areas become space planning identifiers (SPIs). These may be GT cells, functional or product-focused cells, support activities, or relevant activities outside the scope of the project. The focus criteria selected should be consistent with corporate goals, market strategy, manufacturing processes, and infrastructure. Developing such focus is one of the most important elements of manufacturing strategy and provides a firm basis on which the facility layout is established. Focus is our best means for reducing manufacturing complexity and for directing technical and knowledge resources to meet customer demands. In this way manufacturing is made an important part of the product mix rather than a hapless supplier of commodities.

The strategic analysis lays the foundation for the layout. The focus analysis identifies opportunities for focused manufacturing and a policy for focus. The manufacturing strategy guide sheet assists the layout team development of a policy-level strategy statement. This in turn guides the project team in its layout design. The manufacturing/operation strategy statement and its updates will also guide operating people as they make day-to-day decisions across the broad areas of process, facilities, and infrastructure.

The layout should incorporate and support the manufacturing strategy and the *business idea* of the firm. If the layout fails to do so, it will induce, at the very least, considerable stress.

At worst, the manufacturing system may fail to meet market requirements and risk failure of the entire firm.

Infrastructure Analysis

Process refers to the equipment and operations that work directly on the product to add value. The manufacturing strategy statement recommends an appropriate scale for equipment. It makes general recommendations on technology types, ease of setup, and ranges of product capability. It should also address quality capability. There is strong correlation between facility design, good manufacturing practice, and quality systems that meet ISO 9000 requirements.

Operating infrastructure supports the manufacturing process. It includes production control, human resources, information systems, accounting, maintenance, and other functional areas of the business. These infrastructural activities are often the most dissonant for many reasons beyond the scope of this chapter, yet space must be provided for them in the new facility. Facilities are the *physical* infrastructure. Buildings, utilities, roads, and land support the process. These, too, should fit with the other elements of the manufacturing system. For example, a strategy that depends on cellular manufacturing and new product flexibility requires a layout, building, and electrical system that can easily change to accommodate new products, new cells, and changed volumes.

THE LAYOUT PROCESS

The facilities layout process of the generic project plan translates existing knowledge and agreed to focus and manufacturing strategies into a facility layout. This procedure includes the definition of space planning identifiers (representations of activities) that establish the organization and purpose of the layout. The designers analyze capacity requirements and review the processes.

Next, material flows must be quantified, space requirements calculated, and constraints identified. Incorporating this information in progressive diagrams eventually leads to macro layout options. Space planning identifiers (SPIs) are representations of specific activities and are used to sort out and clarify the many factors and influences that result in the listing of all the major activities to be included in the layout. The SPI is the most fundamental planning element. Strategic facilities planning also adds improved data analysis, strategic considerations, techniques that organize constraints, and evaluation of design options. The fundamental elements of every layout project are space planning identifiers, affinities, space, and constraints. From the analysis of these elements, configuration diagrams, layout primitives, macro layout options, and populated layouts are eventually derived.

The first layout element is the space planning identifier. Most projects require 15 to 35 SPIs. If more appear necessary, the project scope may need to be changed so that the first stage develops a macro, large block space planning unit (SPU) layout, and the second stage develops a macro, small block SPU layout for each of the previous large blocks. An SPU adds space to an SPI. It may be a product-focused cell, such as a concrete saw assembly cell; a functional department, such as a powder paint unit; a storage area, such as a tool crib; or a building feature, such as a loading dock.

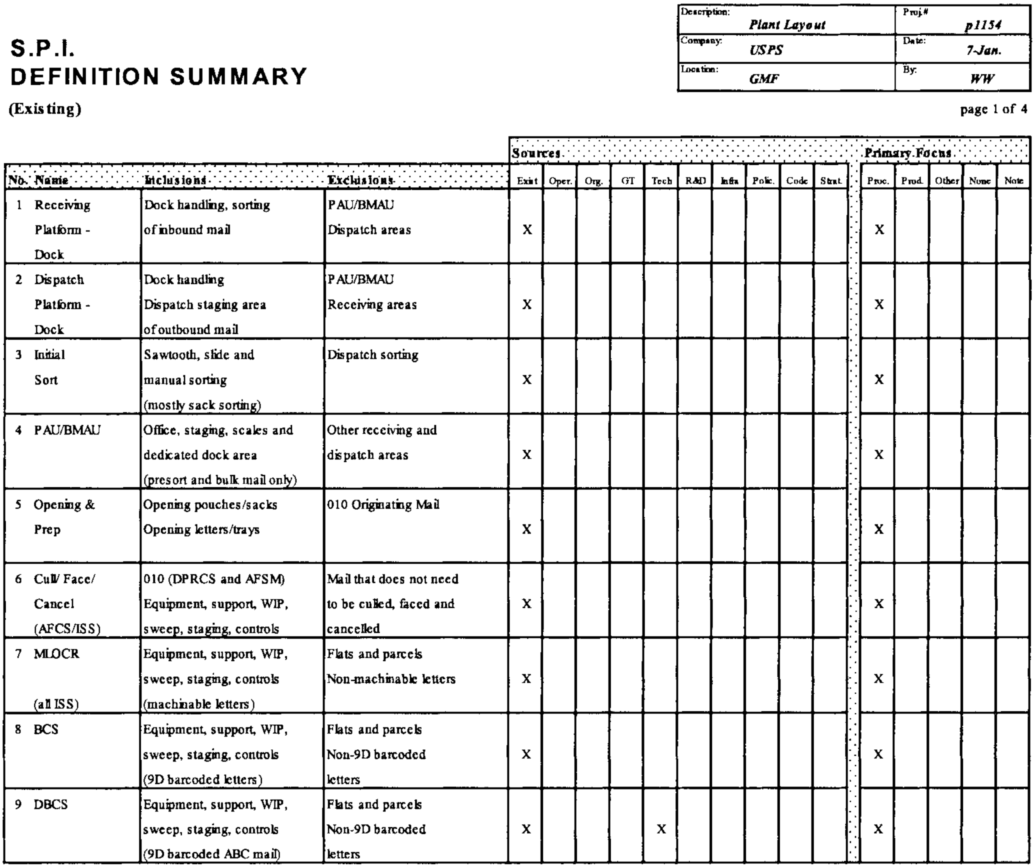
Develop SPIs

The following 12 sources can be used to develop SPIs:

1. Existing SPIs
2. Operation maps

3. Organization charts
4. Group technology
5. Technology forecasting
6. Research and development
7. Infrastructure
8. Company policy
9. Codes and regulations
10. Company strategy
11. Customer requirements
12. Benchmarking

The example given in Fig. 8.2.7 is a useful way to record the SPI definitions in summary form. In the first column each SPI is given a unique identity number. The second and third columns identify activities that are included and excluded. A source listing on the right-hand side of the form also gives the primary focus for each SPI.



S.P.I.
DEFINITION SUMMARY
(Existing)

Description:	*Plant Layout*	Proj.#	*p1154*
Company:	*USPS*	Date:	*7-Jan.*
Location:	*GMF*	By:	*WW*

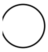
page 1 of 4

No.	Name	Inclusions	Exclusions	Sources										Primary Focus				
				Exist	Oper.	Org.	GT	Tech	R&D	Infra	Polic.	Code	Strat.	Proc.	Prod.	Other	None	Note
1	Receiving Platform - Dock	Dock handling, sorting of inbound mail	PAU/BMAU Dispatch areas	X										X				
2	Dispatch Platform - Dock	Dock handling Dispatch staging area of outbound mail	PAU/BMAU Receiving areas	X										X				
3	Initial Sort	Sawtooth, slide and manual sorting (mostly sack sorting)	Dispatch sorting	X										X				
4	PAU/BMAU	Office, staging, scales and dedicated dock area (presort and bulk mail only)	Other receiving and dispatch areas	X										X				
5	Opening & Prep	Opening pouches/sacks Opening letters/trays	010 Originating Mail	X										X				
6	Cull/ Face/ Cancel (AFCS/ISS)	010 (DPRCS and AFSM) Equipment, support, WIP, sweep, staging, controls	Mail that does not need to be culled, faced and cancelled	X										X				
7	MLOCR (all ISS)	Equipment, support, WIP, sweep, staging, controls (machinable letters)	Flats and parcels Non-machinable letters	X										X				
8	BCS	Equipment, support, WIP, sweep, staging, controls (9D barcoded letters)	Flats and parcels Non-9D barcoded letters	X										X				
9	DBCS	Equipment, support, WIP, sweep, staging, controls (9D barcoded ABC mail)	Flats and parcels Non-9D barcoded letters	X				X						X				

FIGURE 8.2.7 SPI definition summary. (*Courtesy of The Leawood Group 92458/95086.*)

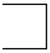
Classify SPIs

SPIs are classified by purpose or the activity that they represent. In this process an extended version of the American Society of Mechanical Engineering (ASME) Process Charting Symbols is used.

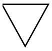


The circle, or operation symbol, represents an operation such as product assembly.

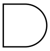
A right-pointing arrow, or transport symbol, represents a material movement activity such as that at a shipping dock.



The square inspection symbol indicates a test or inspection operation.

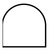


The storage activity symbol is the inverted triangle or hopper.

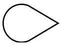


The letter *D,* temporary storage symbol, represents work in process, set down, or staging.

An upward pointing arrow identifies an office.



A letter *D* rotated 90° is a service symbol.



The combination of operation and material movement symbols provides a pear drop shape, symbolizing handling. This is a very useful symbol showing where handling work has to be done that does not add value directly to the product.

Develop Affinities

The next step in the layout process is to determine affinities. Affinities are the degree of attraction between SPI pairs that lead to the layout configuration. They represent a requirement for proximity between each pair of SPIs (cells or activities) in a layout. Affinities may be positive, negative, or neutral. Positive affinities indicate attraction and that closeness is required. Negative affinities indicate that separation is desirable or necessary. Affinities arise from material flow and nonflow factors. The following steps are used to develop affinities:

- Calibrate material flows.
- Determine nonflow affinities.
- Combine flow and nonflow affinities.
- Evaluate and review affinity proportions.

Material Flow Calibration

Material flow calibrations follow from the material flow analyses. Material flow intensities, in a common equivalent flow unit between SPI pairs, are converted into affinities based on flow only by transferring material flow data from a from-to chart to a ranked bar chart, as depicted in Fig. 8.2.8, and by calibrating the flows into an A, E, I, O, U format.

The ranked bar chart typically indicates a Pareto distribution, a few important high-intensity flow paths, and many trivial low-intensity flow paths. The few high-intensity flows will have a significant effect on the layout design; other flows may modify the layout.

FACILITIES LAYOUT AND DESIGN

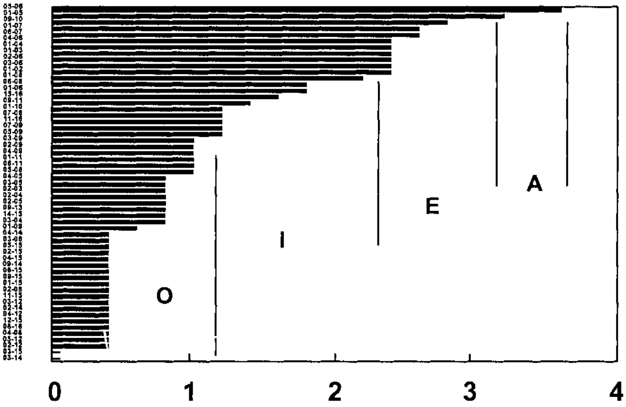


FIGURE 8.2.8 Material flow ranked bar chart.

Nonflow Affinities

Material flow is a major determinant of layout design. For most layouts nonflow affinities are also an important consideration for several reasons:

- Environmental constraints and concerns
- Process similarities
- Shared equipment
- Shared supervision or management
- Shared workforce
- Product quality enhancement
- Utility distribution
- Security and hazard concerns
- Fitting the manufacturing/corporate strategy
- Codes and regulations
- Company image
- Communication between SPIs

Each project reveals other unique causes that create affinities. The vowel convention scale used for calibrating material flow is used to rate the nonflow affinities. The scale is extended for negative affinities. Proximity values are listed with generally accepted understanding of their meanings:

A = absolute proximity—adjoining
E = especial proximity—close, touching if possible
I = important proximity—nearby
O = ordinary proximity—somewhere conveniently near
U = unimportant proximity—doesn't matter
X = proximity is not desirable—keep apart
XX = separation is important—must be kept apart

Because the determination of nonflow affinities is a matter of judgment, it is useful to develop benchmark affinities. These can be a basis for judging all other affinities. The following manufacturing example shows typical benchmark affinities.

Affinities	SPI pairs	Basis for proximity
A	Coil storage and shear	Similar handling problems
	Clean and paint	Avoids contamination
E	Primary and secondary painting	Share materials, share equipment, similar skills
I	Subassembly and final assembly	Control
O	Wire department and stores	Convenience
U	Harness assembly and toolroom	Infrequent contact
X	Product assembly and design	Noise
XX	Welding and solvent storage	Fire hazard

Material flow ratings are the result of quantitative analysis but nonflow ratings are subjective. Planners, managers, supervisors, and employees are sources of informed opinion for developing nonflow data. Considerable difficulty can occur in collecting the necessary input from each source. The three most common methods for collecting these data are interviews, surveys, and consensus meetings. Each method has its own advantages and disadvantages. Interviews have the benefit of face-to-face interaction. However, interviews can be lengthy and time-consuming and can lead to extensive cross-checking and adjustments. Using survey forms is a quick means of gathering data. This method provides input from people who are unavailable for interviews. However, surveys result in few responses and questionable, often biased, results. Individuals who respond probably know their own jobs very well, but that is no guarantee that their judgments of affinities with other SPIs are sound. The most reliable method is the consensus meeting. The participative approach fosters cooperation and provides additional information. A chart such as the one used in Fig. 8.2.9 is a useful way to record affinities. The procedure for entering the data is as follows:

1. Record the project identification data in the project block at the top right.
2. Fill in the reasons for the affinities in the reasons box. A useful convention is to make material flow reason 1. Other reasons, which can vary from project to project, can be entered at the start or as they arise.
3. List the SPIs down the left column.
4. Record the affinity in the appropriate intersect.
5. Record the basis or bases for choosing the affinity rating.

Figure 8.2.10 shows the intersects on an enlarged scale for SPI numbers 1 and 2, Incoming Platform and Letter Process A. The procedure for filling in this diamond is:

1. Place the affinity rating between SPIs 1 and 2 in the top half of the diamond. Here, it is E.
2. Fill in the bases for this affinity in the bottom half of the diamond. Here, numbers 1 and 4.

FACILITIES LAYOUT AND DESIGN

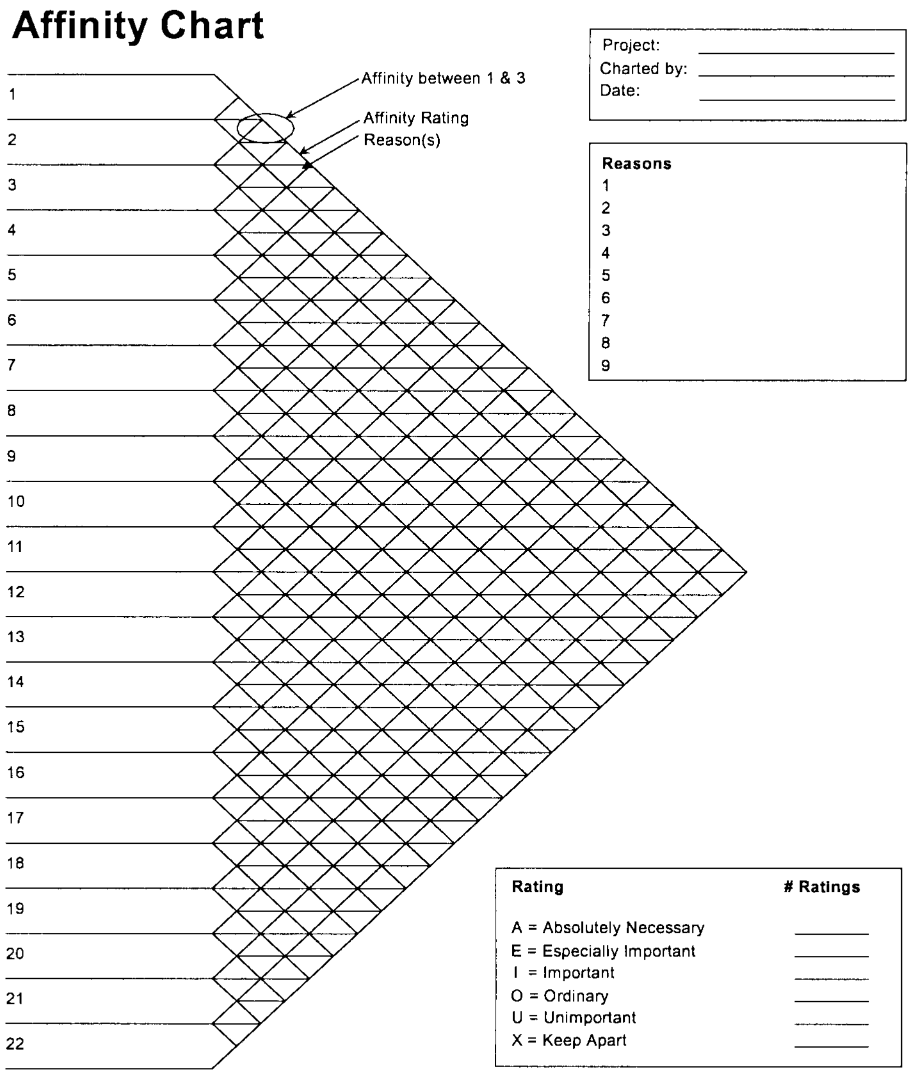

Affinity Chart
Project:
Charted by:
Date:
Affinity between 1 & 3
Affinity Rating
Reason(s)
1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16
17
18
19
20
21
22
Reasons
1
2
3
4
5
6
7
8
9
Rating
# Ratings
A = Absolutely Necessary
E = Especially Important
I = Important
O = Ordinary
U = Unimportant
X = Keep Apart

FIGURE 8.2.9 Affinity chart. (*Courtesy of The Leawood Group 90301.*)

Combined Affinities

Combined affinities are the result of merging flow ratings with nonflow affinities, as in the following procedure:

1. Determine the flow to nonflow ratio.
2. Multiply flow rating by weight or ratio.
3. Multiply nonflow ratings by weight.
4. Sum flow and nonflow scores.

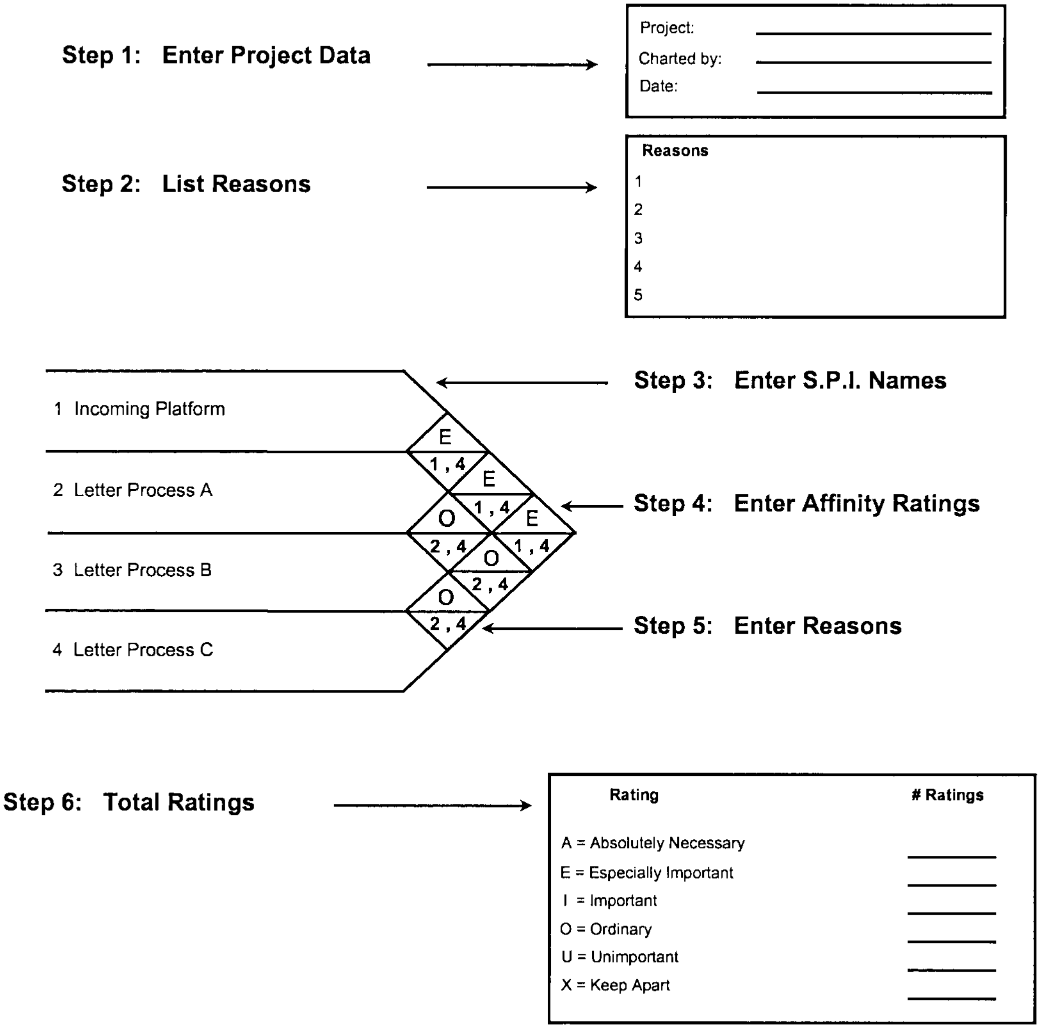

Step 1: Enter Project Data
Project:
Charted by:
Date:
Step 2: List Reasons
Reasons
1
2
3
4
5
Step 3: Enter S.P.I. Names
1 Incoming Platform
2 Letter Process A
3 Letter Process B
4 Letter Process C
E
1,4
E
1,4
E
1,4
O
2,4
O
2,4
O
2,4
Step 4: Enter Affinity Ratings
Step 5: Enter Reasons
Step 6: Total Ratings
Rating
# Ratings
A = Absolutely Necessary
E = Especially Important
I = Important
O = Ordinary
U = Unimportant
X = Keep Apart

FIGURE 8.2.10 How to complete an affinity chart. (*Courtesy of The Leawood Group 92372r.*)

5. Place scores on ranked bar chart.
6. Calibrate total affinities.

The flow to nonflow ratio varies from project to project and from industry to industry. The designer decides the weight or relative importance in each case. Typical ratios of flow to nonflow affinities range from 1:1 to 2:1. However, it has been found over many years of practical application in a wide range of industries that a flow to nonflow ratio of 1:1 is by far the most common. Putting a heavier weight on flow and a lighter weight on nonflow affinities can result in downgrading nonflow values (particularly As and Es) so that they have little impact. This downgrading can result in major upsets with consensus participants.

Applying the selected weighting to the flow and nonflow affinities, steps 2 through 4, provides a merged affinity. This is done by building a matrix of flow and nonflow ratings. Weight is multiplied by each of the numerical values of the flow and nonflow ratings; then the two products are added. The matrix in Fig. 8.2.11 uses a 2:1 flow to nonflow ratio.

The X values flag negative closeness. The numerical value of –1 for an X cannot be subtracted from a flow value of A (4) to give a resulting affinity of E (4 – 1 = 3). The issue must be dealt with in a nonarithmetic way. The solution may result in a fire wall or curtain, or a process change. An affinity combination example of the process is shown in Fig. 8.2.12.

Figure 8.2.13 is an example of combined affinities from an actual project. An affinity frequency distribution should display a few A ratings, progressively larger numbers of Es, Is, Os, and Us, and a few Xs and XXs. The distribution of the combined affinity ratings should be within certain limits. The following distribution for a process-focused layout is typical:

Affinity Rating	**%**
A	1 to 3
E	2 to 5
I	3 to 8
O	5 to 15
U	0 to 85
X XX	0 to 10

High-tech electronic industries may cause higher percentages of X and XX ratings because of special radio/electronic interference. With a product-focused layout, total affinities and high-level affinities (As and Es) will probably be fewer. This is because of simpler material flows and communication lines in a product-focused layout. In a functional or process-focused layout there are more lines of communication and heavier, more complex material flows between major departments. The result is a higher number of total and high-level affinities. If a nontypical affinity distribution occurs, it is necessary to review the ratings.

		Nonflow										
		4	3-1/2	3	2-1/2	2	1-1/2	1	1/2	0	-1	-2
Flow		A	A-	E	E-	I	I-	O	O-	U	X	XX
8	A	12	11-1/2	11	10-1/2	10	9-1/2	9	8-1/2	8	*	*
7	A-	11	10-1/2	10	9-1/2	9	8-1/2	8	7-1/2	7		
6	E	10	9-1/2	9	8-1/2	8	7-1/2	7	6-1/2	6		
5	E-	9	8-1/2	8	7-1/2	7	6-1/2	6	5-1/2	5		
4	I	8	7-1/2	7	6-1/2	6	5-1/2	5	4-1/2	4		
3	I-	7	6-1/2	6	5-1/2	5	4-1/2	4	3-1/2	3		
2	O	6	5-1/2	5	4-1/2	4	3-1/2	3	2-1/2	2		
1	O-	5	4-1/2	4	3-1/2	3	2-1/2	2	1-1/2	1		
0	U	4	3-1/2	3	2-1/2	2	1-1/2	1	1/2	0	-1	-2

Note: X values cannot be subtracted from flow values

FIGURE 8.2.11 Flow to nonflow matrix.

Affinity Combination

Description:	New Layout	Project:	1162
Company:	Mail CO	Date:	7-2
Location:	New Facility	By:	WW

		Material Flow			Nonflow			Total	Comb.
From	To	Rating	Wt.	Score	Rating	Wt.	Score	Score	Rating
5	6	4	.66	2.6	4	.34	1.4	4.0	A
1	5	4	.66	2.6	3	.34	1.0	3.6	A
9	10	3	.66	2.0	3	.34	1.0	3.0	E
1	7	3	.66	2.0	2	.34	0.7	2.7	E
6	7	2	.66	1.3	4	.34	1.4	2.7	E
4	6	3	.66	2.0	1	.34	0.3	2.3	E
1	4	3	.66	2.0	1	.34	0.3	2.3	E
1	3	3	.66	2.0	1	.34	0.3	2.3	E
2	6	3	.66	2.0	1	.34	0.3	2.3	E
3	6	2	.66	1.3	3	.34	1.0	2.3	E
1	2	2	.66	1.3	3	.34	1.0	2.3	E
1	8	2	.66	1.3	3	.34	1.0	2.3	E
6	8	2	.66	1.3	2	.34	0.7	2.0	I
1	6	2	.66	1.3	2	.34	0.7	2.0	I
15	16	1	.66	0.7	2	.34	0.7	1.4	I
9	11	1	.66	0.7	2	.34	0.7	1.4	I
1	10	2	.66	1.3	0	.34	0.0	1.3	I
7	8	2	.66	1.3	0	.34	0.0	1.3	I
11	16	2	.66	1.3	0	.34	0.0	1.3	I
7	9	2	.66	1.3	0	.34	0.0	1.3	I
5	9	2	.66	1.3	0	.34	0.0	1.3	I
3	9	1	.66	0.7	1	.34	0.3	1.0	O
2	9	1	.66	0.7	1	.34	0.3	1.0	O
4	9	1	.66	0.7	1	.34	0.3	1.0	O
1	11	1	.66	0.7	1	.34	0.3	1.0	O
6	11	1	.66	0.7	1	.34	0.3	1.0	O
5	8	1	.66	0.7	1	.34	0.3	1.0	O
4	5	1	.66	0.7	0	.34	0.0	0.7	O
2	3	1	.66	0.7	0	.34	0.0	0.7	O
2	4	1	.66	0.7	0	.34	0.0	0.7	O
2	5	1	.66	0.7	0	.34	0.0	0.7	O
9	13	1	.66	0.7	0	.34	0.0	0.7	O
14	15	1	.66	0.7	0	.34	0.0	0.7	O

Note: **List continues with over 100 other "U" ratings.**
Xs are handled on an individual basis.

FIGURE 8.2.12 Affinity combination.

Configuration Diagrams

Configuration diagrams are derived from SPIs and affinities. Figure 8.2.14 is an example. The diagram is a nodal representation of a layout or a layout without space. It is a logical step in a structured layout process. The source information for developing the configuration diagram is the combined rating affinity chart, Fig. 8.2.13. The number of lines indicate the affinity between the SPIs. The rating lines are considered as rubber bands, with the A rating giving the strongest pull as four bands would do. Those with E (3), I (2), or 0 (1) ratings would have lesser pulls and can be farther apart. X ratings are connected with wiggly lines, representing a spring

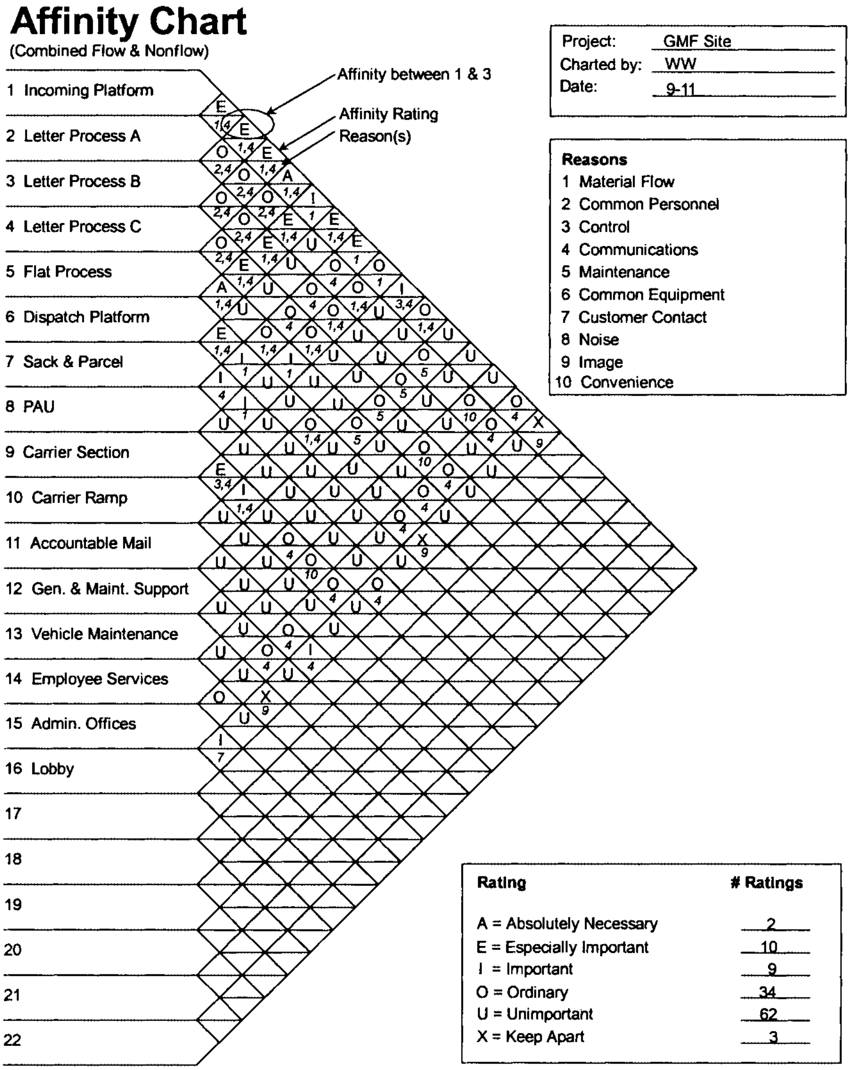

Affinity Chart
(Combined Flow & Nonflow)
1 Incoming Platform
2 Letter Process A
3 Letter Process B
4 Letter Process C
5 Flat Process
6 Dispatch Platform
7 Sack & Parcel
8 PAU
9 Carrier Section
10 Carrier Ramp
11 Accountable Mail
12 Gen. & Maint. Support
13 Vehicle Maintenance
14 Employee Services
15 Admin. Offices
16 Lobby
17
18
19
20
21
22
Affinity between 1 & 3
Affinity Rating
Reason(s)
Project: GMF Site
Charted by: WW
Date: 9-11
Reasons
1 Material Flow
2 Common Personnel
3 Control
4 Communications
5 Maintenance
6 Common Equipment
7 Customer Contact
8 Noise
9 Image
10 Convenience
Rating
# Ratings
A = Absolutely Necessary 2
E = Especially Important 10
I = Important 9
O = Ordinary 34
U = Unimportant 62
X = Keep Apart 3

FIGURE 8.2.13 Combined affinities chart. (*Courtesy of The Leawood Group 90301-1/93089.*)

pushing them apart. For X affinities, one wiggly line (to represent a coiled spring) is used, and for XX affinities, two wiggly lines are used.

Figure 8.2.15 presents the steps in developing the configuration diagram. First, the As and Es are placed. The As have four lines between them; the Es have three. Then Is are added, and the diagram is then redrawn. A good way to do this is to look for hubs and terminals, rearranging and adding Os and Xs. The diagram is rearranged for the best fit. SPI pairs are identified by number and activity symbol. Single or multiple lines connect the SPI symbols.

On many layout projects, particularly large ones, the need to provide access to rest rooms, break areas, supervisors' offices, portable equipment staging areas, maintenance, and so on can cause serious skewing problems when configuration diagrams are developed. These func-

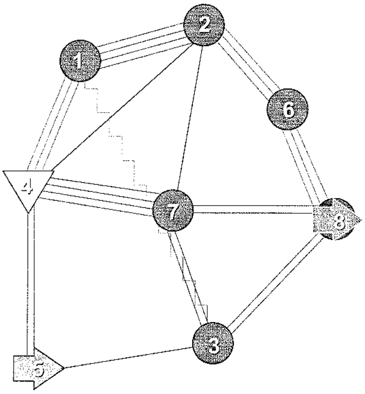


FIGURE 8.2.14 Configuration diagram.

tions are listed as SPIs; space is required for their SPUs in the macro layouts. Almost every other SPI will show an affinity to them, usually as Is or Os. It is advantageous to divide the SPIs into two groups:

1. Primary activities that relate to adding value: receiving, storage, inspection, shipping, and so forth.
2. Secondary activities that are necessary to the operation of the organization but do not directly contribute to making and distributing the product.

The configuration diagram is developed for the primary activities only. Then an overlay (or series of these showing different options) is used to show how the secondary functions can fit without skewing the primary configuration diagram. Often this results in splitting up rest room, break area, staging area, and other SPIs into several parts (A, B, C, . . .) rather than constraining them into single point nodes.

The configuration diagram results from the fundamental elements of SPIs and affinities. The inclusion of all flow-based affinities based on existing methods in developing the configuration diagram can lead to distorted layouts for new lean operations. In many high-tech automated operations, the proportion of product flow intensity to total material flow is quite low. Major flows tend to be such materials as dunnage, empty containers, and packaging. But since the primary aim is to maximize the product stream velocity, the layout should be geared to its flow and to achieving fast response. In contrast, a group of facility planners in the automotive industry were impressed by the material-handling system for metal waste in a plant they visited overseas and were considering planning their pressroom and machining area around such a system. They were more than taken aback when we asked them what business they were in—scrap metal? It is *not* the objective to optimize nonproduct flow velocity at the expense of maximizing product flow.

Develop Space

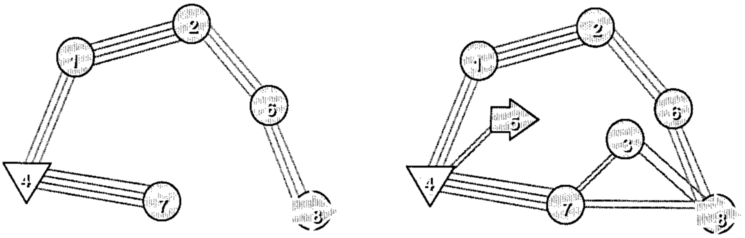
Space is one of the four basic elements of every layout. The space on existing layouts is a matter of record, the space for new layouts has to be determined. Designers of a new layout first develop the SPIs and their affinities, then calculate space. The SPI plus space equals a space planning unit (SPU). Six methods are available for computing space:

1. Elemental calculation
2. Standard data
3. Transformation
4. Visual estimating
5. Proportioning
6. Ratio forecasting

These methods give the designer a toolbox from which to select the most appropriate method or methods. Each SPI may require a different method for establishing the space needed. The accuracy level required for space calculations varies widely. The level of effort, credibility, and time horizon also varies for each method.

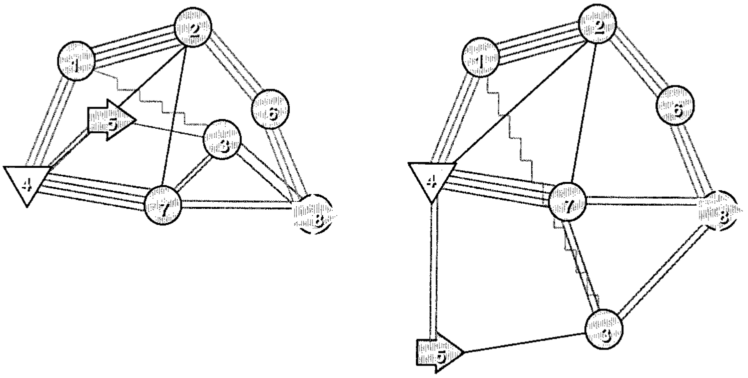
Elemental Calculation. Figure 8.2.16 illustrates the approach to elemental calculation. In this method the space for each process, item of equipment, and aisle is collected. The total is the SPU space. Elemental calculation is used for small areas with few items or where a

FACILITIES LAYOUT AND DESIGN



A's and E's

Add I's



Rearrange and add O's and X's

Rearrange for best fit

FIGURE 8.2.15 Configuration diagram steps.

few items dominate space requirements. It is also used where space standards do not exist. Elemental calculation requires a complete list of equipment and other needs. For large or complex layouts, this method is laborious. The accuracy of elemental calculation reflects the accuracy of the equipment and furniture list and their measurements. The computed space can be quite accurate when based on an accurate and stable list. However, inaccuracy will result from an inaccurate list or from a functional manager's inflated opinion of departmental importance.

Standard Data Calculation. This is a close cousin to elemental calculation. With the standard data method the designer takes known units such as persons, automobiles, or product and calculates the space from this known space information. The procedure is illustrated in Figure 8.2.17. Standard data calculation is the method of choice for large firms that tend toward many rearrangements. Once the standard data are complete and approved, space calculations are fast and accurate. The following procedure is recommended for developing new space standards:

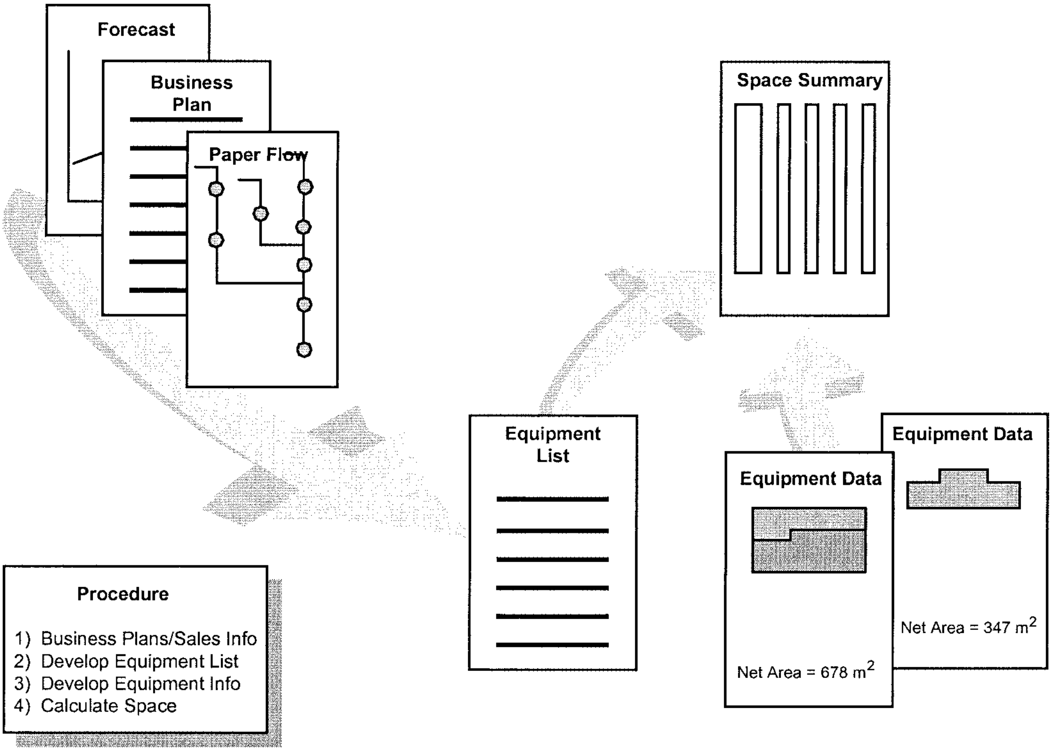

Forecast
Business Plan
Paper Flow
Space Summary
Equipment List
Equipment Data
Equipment Data
Net Area = 678 m²
Net Area = 347 m²
Procedure
1) Business Plans/Sales Info
2) Develop Equipment List
3) Develop Equipment Info
4) Calculate Space

FIGURE 8.2.16 Elemental calculation.

1. Identify complaints/symptoms of nonstandardization.
2. State objectives.
3. Survey current situation and reconfirm objectives.
4. Develop data using regression analysis and synthesis.
5. Gain approval.

This method, like elemental calculation, reflects the accuracy of the data. When the data are accurate and the standards are valid, the space calculation is highly accurate. Where standards are nonexistent their development can be difficult and time-consuming. In situations where furniture and equipment is nonstandard, the elemental method should be used.

Transformation. This is the most versatile of the six methods, particularly for macro and site-level layouts. With an experienced layout designer, the method is reasonably accurate. It is simple and does not require complete furniture, equipment, or personnel lists. The method is illustrated in Fig. 8.2.18. To estimate the space for a particular layout unit, the analyst begins with a comparable existing space. He or she then adjusts, or normalizes, the existing space to account for abnormal current conditions (too tight, too loose, unsafe). The analyst reviews business forecasts, operating plans, and task definitions. If this review reveals changes in activity levels that will have an effect on space, he or she adjusts the normalized space up or down to allow for these conditions.

FACILITIES LAYOUT AND DESIGN

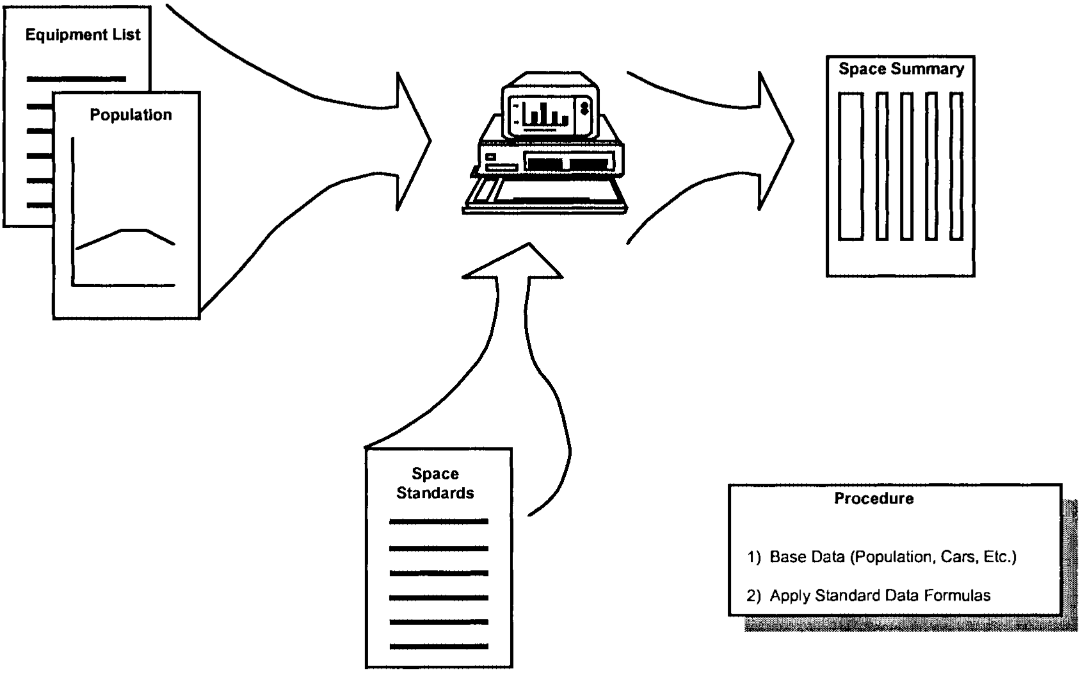

Equipment List
Population
Space Summary
Space Standards
Procedure
1) Base Data (Population, Cars, Etc.)
2) Apply Standard Data Formulas

FIGURE 8.2.17 Standard data calculation.

Visual Estimating. In Fig. 8.2.19 the use of templates and the visual experience of the designer to estimate space is illustrated. The method is fast and has moderate accuracy and high credibility. The designer does not require a complete furniture and equipment list but does require a high experience level. The approach uses a set of scale templates based on a preliminary furniture and equipment list as the starting point. The templates are arranged on a layout grid with space for aisles, circulation, and miscellaneous equipment. The gross space occupied is the estimate for that particular layout block. This prototype layout is used to determine space requirements only. It is not the final layout and does not consider affinities or constraints. It only visualizes the space required.

Proportioning. Proportioning, illustrated in Fig. 8.2.20, applies the principle of proportioning space use. Classes of space often require a constant proportion. Standards, past practice, experience, or existing layouts may provide such proportions. If so, the designer can use them to calculate space. With known proportions, the method is fast, easy, and accurate. Without known and tested proportions, only the experienced designer should use this method.

Ratio Forecasting. Ratio forecasting has the lowest near-term accuracy of the six methods but has the highest long-term accuracy. Its primary use is for site planning and long-range planning. In stable industries it can produce fair accuracy on 20-year forecasts. The process starts with historical data as visualized in Fig. 8.2.21.

The space is classified and measured by class at several past time intervals. These intervals vary but typically are 5 to 20 years. Ratios are developed by relating the space in each class to some parameter such as sales dollars or site population. The basis parameter should be stable over the historical period and expected to be stable during the forecast period. The ratios of space class to basis parameter often have clear long-term trends. The analyst chooses a set of

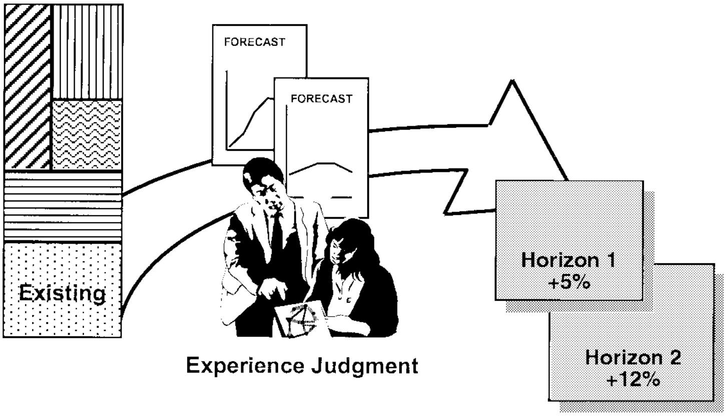

Existing
FORECAST
FORECAST
Experience Judgment
Horizon 1
+5%
Horizon 2
+12%

FIGURE 8.2.18 Transformation.

ratios and projects them. Such projection may use visual or statistical measures. The ratios for future horizons are used to indicate the space required at that horizon. For example, the number of units produced per square meter in a factory in 10 years is projected to be 120 per day. The forecasted daily sales for the product in 10 years is 2.4 million. The estimated production space will be sales per day in 10 years divided by the number of units produced per day per square meter; that is, 2.4 million divided by 120 = 20,000 square meters.

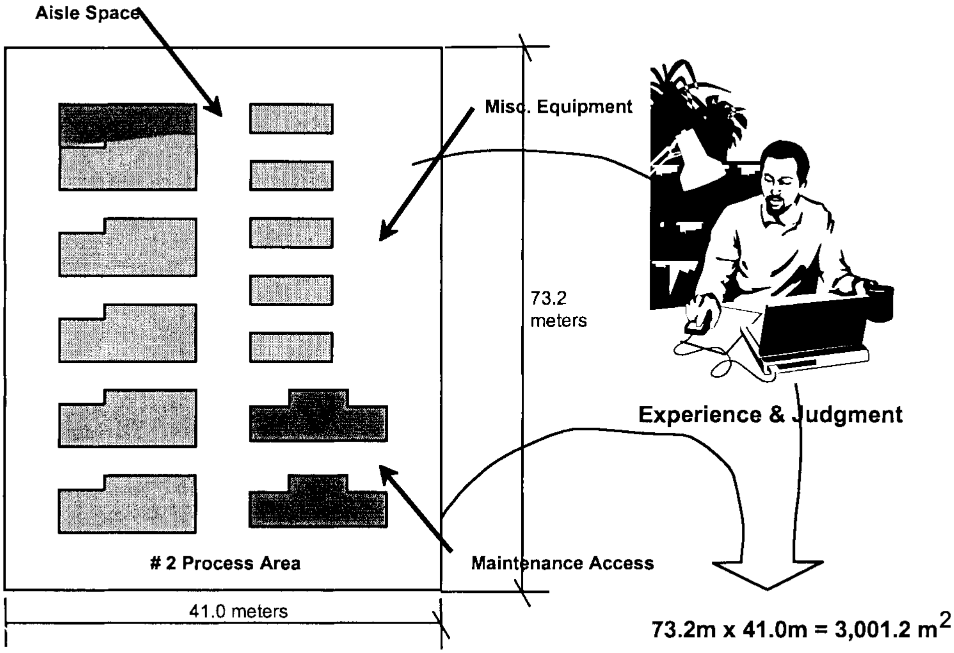

Aisle Space
Misc. Equipment
73.2
meters
Experience & Judgment
# 2 Process Area
Maintenance Access
41.0 meters
73.2m x 41.0m = 3,001.2 m²

FIGURE 8.2.19 Visual estimation.

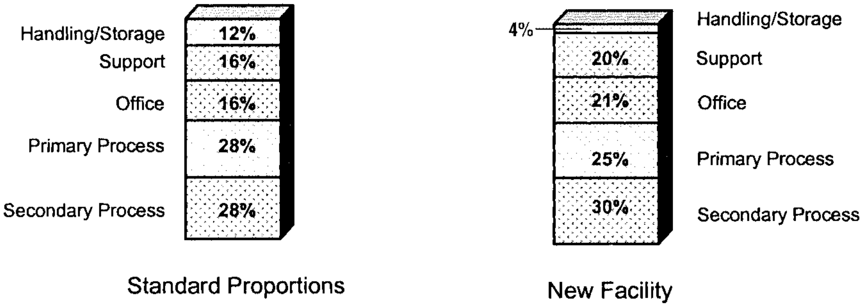


FIGURE 8.2.20 Proportioning.

Hybrid Methods. These methods are combinations of the methods previously described. When computing space the analyst or layout designer normally selects a method for each space planning identifier. Sometimes several methods can combine for good results. The designer also may use more than one method as a cross-check. Space calculations for several SPUs using transformation can then be cross-checked using elemental calculation. Several factors affect the designer's choice of method for determining space. Among these are accuracy, computation effort, experience of the designer, and credibility to the user. Figure 8.2.22 compares the six methods on each of these dimensions.

Large or complex layouts justify higher levels of effort than small and simple layouts. Populated or cell layouts require more effort and greater accuracy than macro or site layouts. Experienced designers may use visual estimating and transformation when the less experienced should use elemental or standard data calculation. Users and managers often consider transformation an unreliable method. In the hands of an experienced designer, however, it is often far more accurate than the forecasts on which elemental or standard data calculations are based. Apart from credibility, accuracy is also important. Factors that affect the required accuracy are design phase, equipment type, business plan uncertainty, and consequences of over- or underestimating.

Typically a design requires less accuracy in the site and macro phases of layout. Two reasons account for this. First, random errors compensate, or bias may cause all SPU sizes to be either over or under the true space requirement. Second, sensitivity to error is less. During the populating of the macro layout in the next phase, refinement corrects small errors.

The uncertainty of input parameters may overshadow the accuracy of some methods. The resulting pseudoaccuracy brings comfort to some but does not improve the uncertainty of the business plan or environment. In an unstable business environment, accuracy is fleeting and flexibility is important.

Layout Primitive

Adding space, determined by one or more of the foregoing methods, to the configuration diagram leads to the derived element layout primitive shown in Fig. 8.2.23. This usually requires adjustment to the configuration diagram to accommodate the different sizes of the space blocks. The block sizes are to scale but normally do not assume the eventual shape of the SPU. If the aspect ratio (length to width) is known, then it can be shown in the layout primitive as required in the final layout. For example, a phosphate wash process size and shape (footprint) is known. It is often helpful at this time to identify clusters of SPUs that logically go together. A separate cluster diagram layout primitive can be useful when the macro layout is developed. The layout primitive is an exploded view of a layout, which leads into the constraint process of developing the macro layout.

FACILITIES LAYOUT AND DESIGN

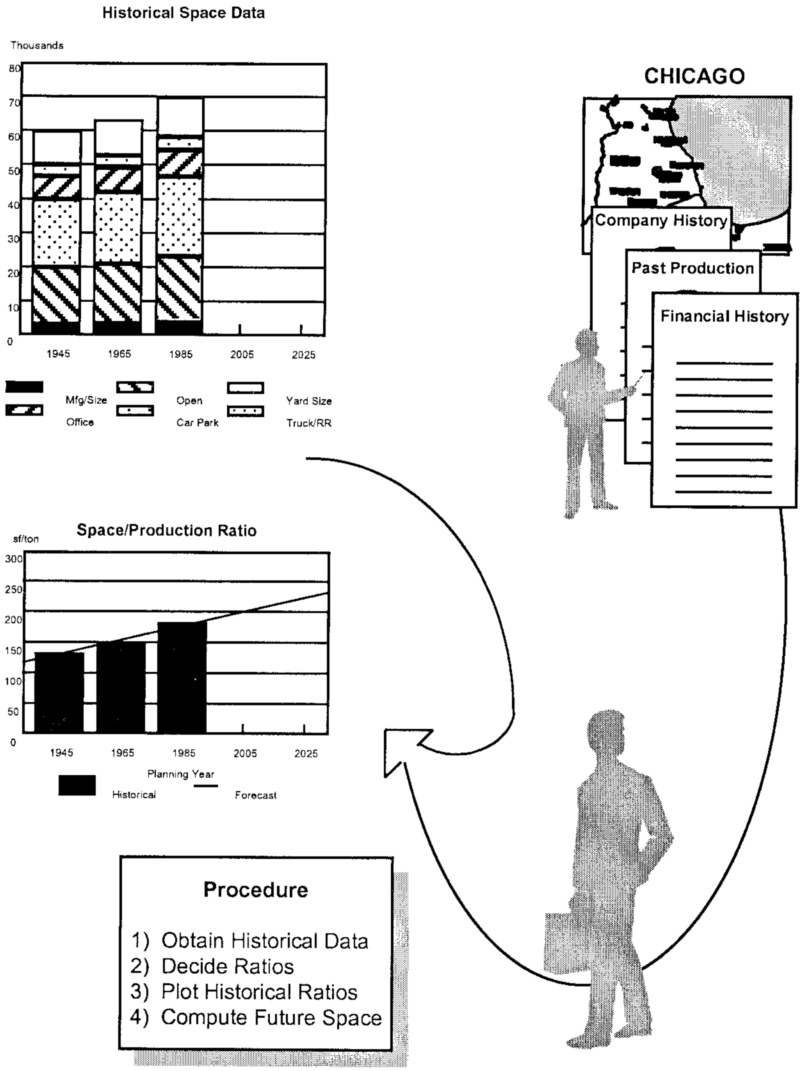

Historical Space Data
Thousands
80
70
60
50
40
30
20
10
0
1945
1965
1985
2005
2025
Mfg/Size
Office
Open
Car Park
Yard Size
Truck/RR
CHICAGO
Company History
Past Production
Financial History
Space/Production Ratio
sf/ton
300
250
200
150
100
50
0
1945
1965
1985
2005
2025
Planning Year
Historical
Forecast
Procedure
1) Obtain Historical Data
2) Decide Ratios
3) Plot Historical Ratios
4) Compute Future Space

FIGURE 8.2.21 Ratio forecasting.

Constraints

Every layout project is subject to some constraints. At this stage of the layout process, the physical constraints such as available space, shape of space, building columns, doorways, and elevators are accommodated. The constraint summary example in Fig. 8.2.24 provides a lead into the constraining process.

This is the step that transforms the layout primitive into macro, or block, layout options. In the constraining process, the facility designer can introduce secondary clusters or review focus parameters. Here, there is an opportunity to divide or combine SPUs. For example, a warehouse may be split into two parts: one part can store purchased parts, and the other part can

Methods	Accuracy	Effort	Planning Horizon	Input Data Complete	Experience Req'd	Credibility
Elemental	High	Very High	Short	Very	Low	High
Standard Data	High	High	Short	Very	Low	High
Visual Estimate	Mod.	Mod.	Med.	Mod.	High	High
Transformation	Mod.	Low	Med.	Mod.	High	Mod.
Proportioning	Mod.	Low	Long	No	Mod.	Mod.
Ratio Forecast	Low	Mod.	Very Long	No	Mod.	Mod.

FIGURE 8.2.22 Selecting a method.

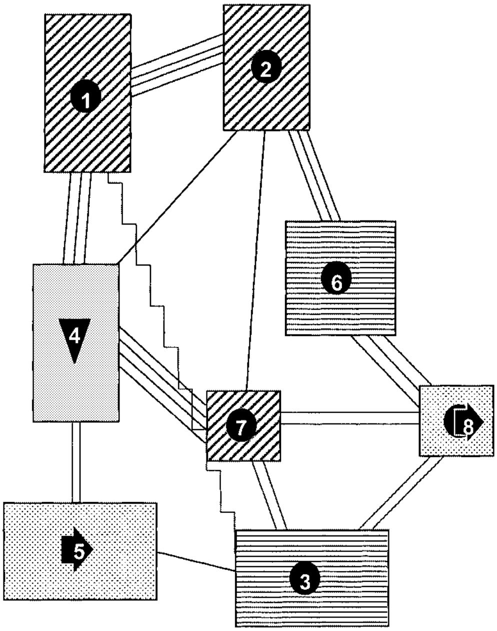


FIGURE 8.2.23 Layout primitive. (© *1990 The Leawood Group 91621.*)

CONSTRAINT SUMMARY

Notes
1. *Customer Service area only*
2.
3.
4.

Description: *Office Layout*
Proj. No: *p1162*
Company: *XYZ Corp.*
Prep By: *WW*
Location: *Central*
Page: *1* of *1*
Date: *15-Jan.*

Constraints

SPU	SPU Name	**Site Conditions**	Visitor Access		**Building Features**	Columns		**Utilities**	Commun. Lines		**Traffic**	Personnel	Paper / Printouts		**Organization**	Appearance		**Security**	Confidential	High Value	Proprietary											
1	Order Entry					X			X											X												
2	Credit					X			X										X													
3	File Storage					X						X							X	X	X											
4	Telemarketing					X			X											X												
5	Design					X													X	X	X											
6	Retail Coordinators					X			X				X							X												
7	Sr. Retail Coordinator		X			X			X				X							X												
8	Mgr. Customer Service		X			X			X			X	X			X				X												
9	Asst.Customer Service		X			X			X			X	X							X												
10	Copy											X																				
11	Fax								X			X																				
12	Computer					X			X			X	X							X												
13	Supplies											X																				
14	Coat Closet											X																				

FIGURE 8.2.24 Constraint summary.

hold finished-goods packaging material. The constraint process can also show options at every step of developing fundamental and derived elements, thus generating layout options. For example, the SPUs can be buildings, factories, factories within factories, departments, or product- or process-focused cells. These choices and combinations of them with differing transformations at the layout primitive to the block layout lead to feasible layout options.

Macro Layouts

The output from the constraint process are macro, or block, layout options. Layout options are sound and different designs that provide managers with choices. The selection of a preferred option tests the extent to which the designer has interpreted the strategic company intent. It can also release additional information that has hitherto not been forthcoming. An example of a macro layout is shown in Fig. 8.2.25. Management approval of a macro layout provides the input for the populated layouts.

Layout Option Evaluation and Selection

Management selects from the macro layouts or synthesizes additional macro layouts from the options presented. With an approved macro layout, material-handling systems can then be designed. The design and approval of populated layouts for each block of the macro layout follow.

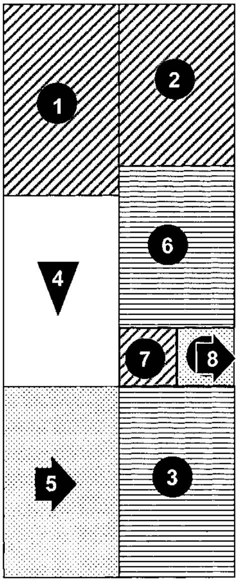


FIGURE 8.2.25 Block layout. (© *1990 The Leawood Group 92174.*)

A formal evaluation process can provide a sound basis for selection of the preferred option. The strategic facilities planning (SFP) process generates sound layout options. The question may be asked: "Why have options?" Managers may want one layout. The cause and benefit of options arise because there is no one correct solution to layout designs, and it is preferable to choose rather than accept or reject. Layout options arise from

- Differing focus concepts and thus different SPIs/SPUs
- Combining or splitting of SPIs/SPUs
- Mirror images
- Single or multistory stacking
- Different or multiple buildings
- Building features
- Operation mode preferences
- Different process technology

Facility Design Objectives

Structuring the evaluation process forces the identification of key factors. For instance, what is wanted? How will it be achieved and how will it be recognized? For design options to qualify for evaluation they must meet fundamental criteria. One way to establish validation criteria is to prepare a list to which management can react. Submitting a preliminary list for consideration saves management time. A process of criteria validation confirms project assumptions and avoids wasted effort caused by unclear project definition. All options to qualify must

- Meet forecast capacity needs
- Be consistent with company image
- Support operations strategy
- Allow for new product introductions
- Provide for rapid material velocity.

Evaluation Methods

For facility layout design option evaluation the following methods are available:

- Sensory
- Intangibles
  PNI (positive, negative, and interesting)
  Ranking
  Weighted-factor analysis
  Kordanz™ method*
- Material flow
  ISO cost/distance intensity

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* Kordanz is a trademark of The Leawood Group, Ltd.

  Quantified flow diagrams
  Simulation
- Affinity analysis
- Decision trees
- Fluidity

The sensory method draws on instinct, experiences, and prejudices. This method requires decision makers experienced in facilities layout design. Whatever the experience in the evaluation team, sensory evaluation is always the first method that individuals use, often subconsciously. Sensory evaluation is a hurdle that all evaluations must overcome before more analytical methods will be considered by the evaluators.

Intangibles include PNI, ranking, weighted-factor analysis, and Kordanz. Features for each option are listed and reviewed. Simple ranking is a nonquantitative method that is useful for elimination of less desirable options.

The weighted-factor method is analytical. The factors can be quantitative or qualitative. Figure 8.2.26 is an example of a weighted-factor evaluation structure. To use the procedure, the project title block is filled in; the layout options to be considered are entered in the Options box; next

1. A list of factors is developed with the evaluators and entered.
2. The decision makers allocate a weight on a 1-to-10 scale to each factor. These are entered in the weight column. Factors can have the same weight.
3. The evaluating panel then considers the factors for each option, rating factors on the A, E, I, O, U, X scale with numerical equivalents of 4, 3, 2, 1, 0, and invalid for X.
4. A weighted score (WS) for each factor is the product of the weight and the rating.
5. When the rating and scoring is complete, the scores are totaled for each option. The highest score gives the preferred option.

The weighted-factor method has many weaknesses:

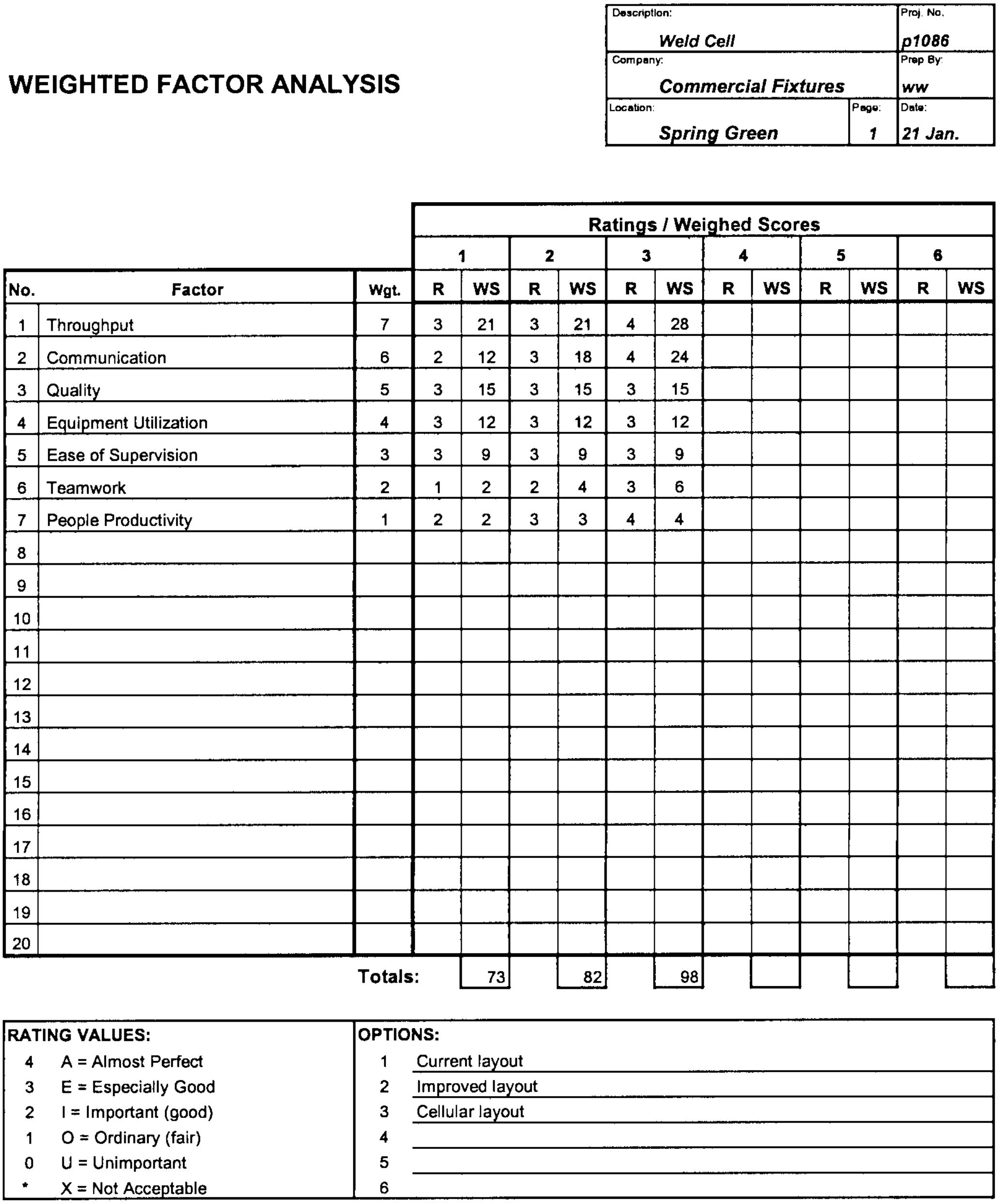
- Factor weighting is subjective.
- The weighting scale is linear.
- There is no measure of evaluation consistency.
- Judging is biased.
- Where panel rating, following discussions, is used, the opinions of a strong personality may influence the judges.
- The method does not create or demand a deep understanding.

But the method does have merit if:

- It develops decision parameters such as factors and their weights.
- It creates meaningful discussion and reduces the range of options.
- The numbers imply a pseudoquantitative quality.
- It provides for many people to arrive at a consensus.
- It often serves its purpose.

The Kordanz method developed by Knott [3] is a computerized form of weighted-factor analysis, which overcomes many of the weighted-factor method shortcomings. It is a multifactor method with many enhancements:

FACILITIES LAYOUT AND DESIGN



WEIGHTED FACTOR ANALYSIS

Description: *Weld Cell*
Proj. No.: *p1086*
Company: *Commercial Fixtures*
Prep By: *ww*
Location: *Spring Green*
Page: *1*
Date: *21 Jan.*

			Ratings / Weighed Scores											
			1		2		3		4		5		6	
No.	**Factor**	**Wgt.**	**R**	**WS**	**R**	**WS**	**R**	**WS**	**R**	**WS**	**R**	**WS**	**R**	**WS**
1	Throughput	7	3	21	3	21	4	28						
2	Communication	6	2	12	3	18	4	24						
3	Quality	5	3	15	3	15	3	15						
4	Equipment Utilization	4	3	12	3	12	3	12						
5	Ease of Supervision	3	3	9	3	9	3	9						
6	Teamwork	2	1	2	2	4	3	6						
7	People Productivity	1	2	2	3	3	4	4						
8														
9														
10														
11														
12														
13														
14														
15														
16														
17														
18														
19														
20														
		Totals:		73		82		98						

RATING VALUES:

4	A = Almost Perfect
3	E = Especially Good
2	I = Important (good)
1	O = Ordinary (fair)
0	U = Unimportant
*	X = Not Acceptable

OPTIONS:

1 Current layout
2 Improved layout
3 Cellular layout
4
5
6

FIGURE 8.2.26 Weighted factor method.

- The evaluation scale is relative rather than absolute.
- It eliminates pseudoaccuracy.
- There is a common basis to compare qualitative and quantitative values.
- The relative importance of the separate objectives of the options is reflected in the final evaluation.
- It calculates level of agreement in probability terms.

The advantages of Kordanz are

- Quantifies opinion
- Tests concordance among evaluators
- Reduces effect of prejudice
- Makes prejudgment difficult
- Encourages participation of specified management levels
- Reduces evaluation to binary decisions
- Captures the knowledge of informed evaluators
- Minimizes time of evaluators
- Separates factor emphasis from evaluation
- Generates confidence among evaluators
- Identifies the relative importance of factors
- Clarifies and polarizes the purpose
- Minimizes emotion
- Is analytical

Figure 8.2.27 charts the Kordanz process. The first step is to decide on the factors. Some examples are shown in Fig. 8.2.28. The Kordanz process achieves factor ranking by forced comparisons between factor pairs. Ties are not allowed. The number of comparisons are $n(n-1)/2$, where n is the number of factors. The ranking is performed by a number of judges. The method tests the consistency of each judge and inconsistencies between them. From the pair comparisons, factor weights by individual, and for all judges, are determined. Following factor weighting, judges are presented with layout option pairs for each factor. They identify the superior option for that factor. The process is repeated for all factors and all options. The system then generates scores for each option for each judge and all judges combined. An example of the results is given in Fig. 8.2.29.

A more comprehensive explanation of evaluation methods is given in Wrennall and Lee [4]. The evaluation process will release more information and understanding of the facility plans. Participation will spread this knowledge and often results in a better hybrid design than each of the evaluated options. Thus follows ownership and acceptance of the layout design.

Populated (Detailed/Micro) Layouts

When details of the individual equipment locations are shown in each block of space, a populated layout results. This step separates the hard space from the soft space and gives meaning to the blocks of the macro layouts. The hard space consists of the footprints of the equipment to be located in the block. The soft space includes access to line-side materials, processes, utilities, maintenance, and exchange of equipment. Macro layouts typically identify main circula-

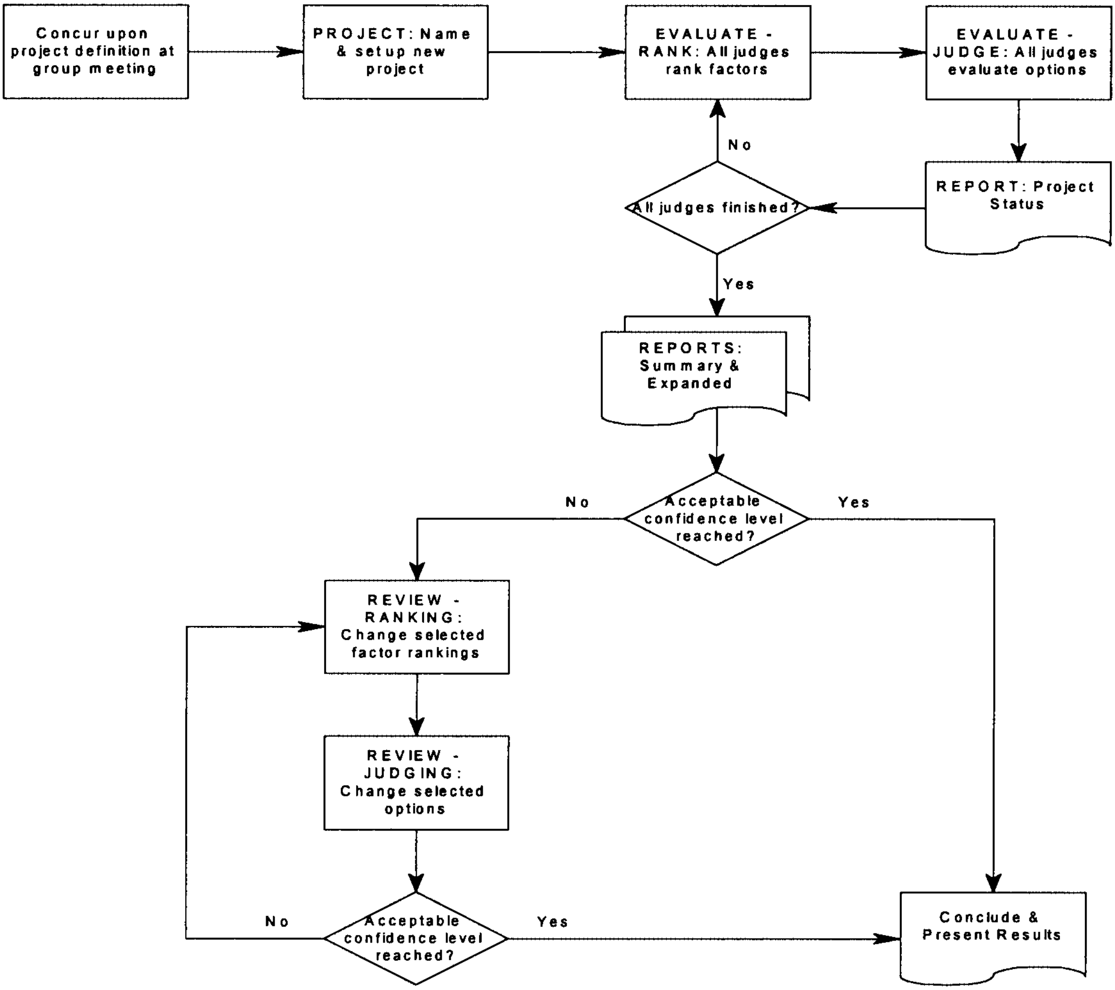

Concur upon project definition at group meeting
PROJECT: Name & setup new project
EVALUATE - RANK: All judges rank factors
EVALUATE - JUDGE: All judges evaluate options
REPORT: Project Status
All judges finished?
No
Yes
REPORTS: Summary & Expanded
Acceptable confidence level reached?
No
Yes
REVIEW - RANKING: Change selected factor rankings
REVIEW - JUDGING: Change selected options
Acceptable confidence level reached?
No
Yes
Conclude & Present Results

FIGURE 8.2.27 Kordanz process.

tion aisles. Working aisles are provided in the populated layouts. Aisles can be categorized as main, secondary, or access aisles. Their width will be determined by the characteristics of the materials, containers, and the material-handling equipment. Aisle allowances based on load sizes are given by Tompkins [5, p. 1790]. Typical aisle widths are

Main aisles	10 ft
Cross aisles	8 ft
Feeder and internal aisles	6 ft

The macro layout blocks consist of workplaces, processes, materials, and circulation space. The major errors in determining space are in allowing sufficient room for material and people movement. Aisle space alone can account for up to 25 percent of total space.

Project: Mail Co Page:1	*Kordanz–Expanded Report* Evaluation by Forced Binary Decision	08/16/96 11:27:45

Project: Mail Co Medium Facility Evaluation

FACTORS

1.	Affinity resolution	Does the option resolve/adhere to affinities?
2.	Minimizes TW	Minimizes the transport work
3.	Aspect ratio met	To what extent does the option meet the 3:2 aspect ratio
4.	Meets company criteria	
5.	Aisle criteria	Safe circulation; ease of material handling; maintains perimeter aisle; SPI access to main aisle
6.	Aesthetics	
7.	Contiguous grouping	
8.	Uniform orient. (SPI)	
9.	Uniform orient. (fac)	
10.	Max. space utilization	
11.	Max. platform access	
12.	Ease of expansion	
13.	Meets focus criteria	Letters, flats, parcel mail loops

FIGURE 8.2.28 Kordanz criteria example.

Block Dynamics

Block dynamics refers to the basis for change within a space planning unit. This depends on constraints such as safety, operating protocols, and block growth patterns. It is inadvisable to plan only for current volumes. The population of SPUs is the study of the required dynamics of a block for today's and tomorrow's capacity. A process for developing populated cell designs is described by Wrennall and Lee [4]. An example of a populated layout is given in Fig. 8.2.30.

Implementation

The next step is to implement the layout design. The layout may be for the rearrangement within an existing plant where the emphasis is on meeting customer needs during the rearrangement—this is often the most difficult. It may be for a move into a vacated building or for a move into a building being built to meet a specific company's needs. For a layout in a vacated or new building, the plant layout must be integrated with refurbishing and/or construction and installation of utilities. For aid in this process, a physical infrastructure checklist is given in Fig. 8.2.31.

Operations

The selected plant layout design leads into the implementation plan that provides the steps for supplying the physical capacity. Plant operations follow. The result of the design and implementation process determines the capability of the plant to achieve the objectives set in phase 1 of the project.

Project: Mail Co	*Kordanz–Expanded Report*	08/16/96
Page:3	Evaluation by Forced Binary Decision	11:27:45

Composite ranking of factors

Factor	Weight
Minimizes TW	69
Affinity resolution	67
Max. platform access	45
Meets focus criteria	41
Contiguous grouping	39
Aisle criteria	37
Meets company criteria	37
Uniform orient. (SPI)	34
Max. space utilization	32
Uniform orient. (fac)	24
Ease of expansion	20
Aspect ratio met	19
Aesthetics	3

Composite ranking of options

Option	Score
Medium option 4	3499
Medium option 2	1862
Medium option 3	1644

Level of confidence: 99.00

An acceptable confidence level was obtained.

FIGURE 8.2.29 Kordanz results example.

GENERAL CONSIDERATIONS

The following features are included in lean layouts. Each deserves special consideration when strategic facilities layouts are being designed.

- Work cells
- Linked production
- Focused factories
- Kanban stock points
- Point-of-use delivery
- JIT material handling
- Reduced space

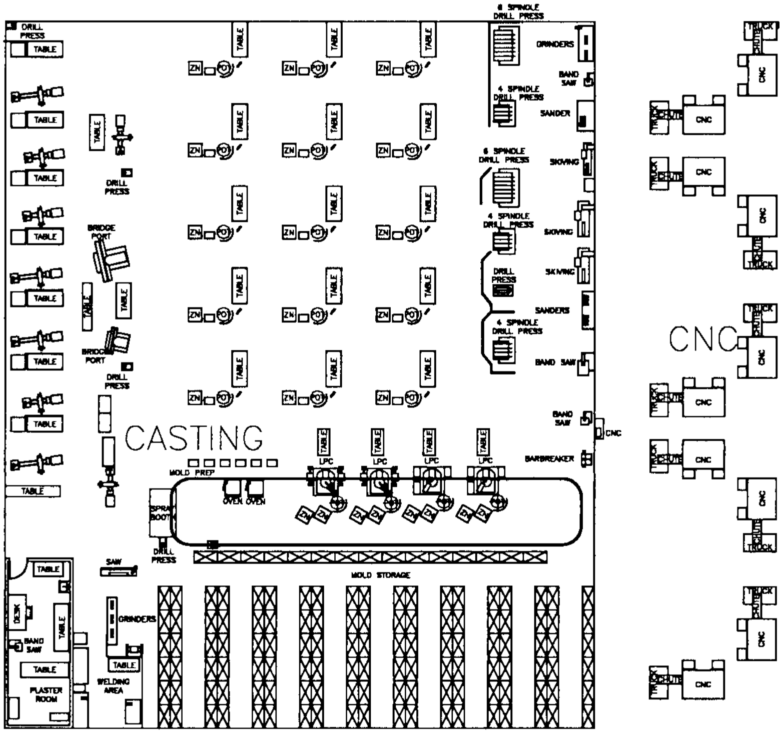

DRILL PRESS
TABLE
BRIDGE PORT
ZN
POT
CASTING
MOLD PREP
OVEN
SPRAY BOOTH
LPC
SAW
MOLD STORAGE
GRINDERS
WELDING AREA
DESK
BAND SAW
PLASTER ROOM
8 SPINDLE DRILL PRESS
4 SPINDLE DRILL PRESS
6 SPINDLE DRILL PRESS
SANDER
SKIVING
SANDERS
BARBREAKER
CNC
TRUCK
CHUTE

FIGURE 8.2.30 Populated layout—functional arrangement of mold prep, casting, and machining areas.

Work Cells

Manufacturing work cells are small self-contained work units that typically build a single product or group of similar products. They typically employ 2 to 12 persons. Ideally they contain all the equipment to manufacture complete products. Work cells balance tasks, encourage teamwork, improve quality, and respond quickly to customer requirements.

Linked Production

In JIT and world-class factories, each process is closely tied to upstream and downstream processes. Processes are physically close and have small inventory buffers between them. Linked production reduces space requirements and improves response time.

Focused Factories

Skinner [6] first presented focused factory concepts more than 20 years ago. These factories limit products, processes, and markets to a manageable range. Focused factories simplify work flow, facilities, and infrastructure. Designers using focus concepts optimize an entire manufacturing system for a specific set of manufacturing tasks. The outcome of focusing operations and a factor that has to be recognized early in the process is the make or buy decisions, or

Physical Infrastructure Checklist

Description:
Proj No:
Company
Date:
Plant
Page: Of:
By:

Utilities

Electrical:
- ☐ Outdoor Substation
- ☐ Indoor Substation(s)
- ☐ Switchgear Room
- ☐ Motor Control Center
- ☐ Uninterruptible Power
- ☐ 115v, 1-ph
- ☐ 208/120v, 3-ph
- ☐ 230v, 1-ph
- ☐ 230v, 3-ph
- ☐ 460v, 3-ph
- ☐ 460/277v, 3-ph
- ☐ Other________________
- ☐ ____________________
- ☐ ____________________

Lighting:
- ☐ High Intensity
- ☐ Low Intensity
- ☐ Natural Light
- ☐ Other________________
- ☐ ____________________

Water/Sewer:
- ☐ Drinking Water
- ☐ Process Water
- ☐ Cooling Tower
- ☐ Water Treatment
- ☐ Wastewater Treatment
- ☐ ____________________
- ☐ ____________________
- ☐ ____________________

Steam:
- ☐ Boiler Room
- ☐ Distribution System

Fuel:
- ☐ Fuel Gas Storage
- ☐ Fuel Gas Mix Plant
- ☐ Oil Storage
- ☐ Coal Yard

Compressed Gas:
- ☐ Air Compressor
- ☐ Surge Tanks
- ☐ Distribution System
- ☐ Oxygen Storage
- ☐ CO2/NO2/Ar/He/Xe
- ☐ Other:_______________
- ☐ ____________________
- ☐ ____________________

Other Utilities:
- ☐ Vacuum
- ☐ Dust Collection
- ☐ ____________________
- ☐ ____________________

____

____

____

Transportation

External:
- ☐ Rail Siding
- ☐ Rail Dock
- ☐ Truck Docks
- ☐ Truck Turnaround
- ☐ Truck Parking
- ☐ Truck Scale
- ☐ Truck Maintenance
- ☐ Road Access/Egress
- ☐ Airport/Heliport
- ☐ Off Site Storage

Internal:
- ☐ Pedestrian Aisles
- ☐ Pallet Truck Aisles
- ☐ Tractor/Fork Trk Aisles
- ☐ Tractor/Fork Trk Repair
- ☐ Battery Charge
- ☐ Overhead Crane
- ☐ Freight Elevators
- ☐ Scale
- ☐ Other:_______________
- ☐ ____________________
- ☐ ____________________

Maintenance

Shops:
- ☐ Electrical/Electronic
- ☐ Mechanical
- ☐ Carpenter
- ☐ Tool & Die
- ☐ Yard Maintenance
- ☐ Other:_______________

Storage:
- ☐ Service Parts
- ☐ Vehicles/Equipment
- ☐ Obsolete Equipment
- ☐ Other:_______________

Administration

- ☐ Visitor/Reception
- ☐ Conference Rooms
- ☐ Customer Service
- ☐ Display Room
- ☐ Training Center
- ☐ Photo/Artwork

Storage:
- ☐ Archives/Tapes
- ☐ Secure Storage
- ☐ Catalogue/Display
- ☐ Microfilm/Microfiche
- ☐ Surplus Furniture/Equip.
- ☐ Other:_______________
- ☐ ____________________
- ☐ ____________________

Human Resources

Administration:
- ☐ Personnel Office
- ☐ Employment Office
- ☐ Credit Union
- ☐ Library
- ☐ Training Facilities

Food Service:
- ☐ Cafeteria
- ☐ Vending Area
- ☐ Lounge/Break Room
- ☐ Executive Dining Room

Health:
- ☐ Exercise Room
- ☐ Jogging Track

Personnel:
- ☐ Toilets
- ☐ Washrooms/Showers
- ☐ Locker Room
- ☐ Water Fountains
- ☐ Public Telephones
- ☐ Employee Parking
- ☐ ____________________

Other:
- ☐ ____________________
- ☐ ____________________

Health And Safety

- ☐ Medical Center
- ☐ Disaster Alarm System
- ☐ Fire Egress
- ☐ Sprinkler Controls
- ☐ Fire Station
- ☐ Tornado/Fallout Shelter
- ☐ Other:_______________
- ☐ ____________________

Production

- ☐ Production Offices
- ☐ Quality Laboratories
- ☐ Gage Calibration
- ☐ Tool Crib
- ☐ Formulation Labs
- ☐ Clean Room
- ☐ Other:_______________

Storage:
- ☐ Packaging Materials
- ☐ Lubricants/Cutting Oil
- ☐ Discrepant Material
- ☐ Incidentals
- ☐ Other:_______________
- ☐ ____________________
- ☐ ____________________

Notes:

FIGURE 8.2.31 Physical infrastructure checklist.

what should be outsourced. These decisions are not just purchasing decisions; they are strategic ones. Bamfield [7] provides three reasons for outsourcing: cost, time, and technological complexity. They all have direct relevance to strategic facilities planning:

- To stop any irrelevant support and consider outsourcing of certain noncore, but essential services.
- To achieve a shorter time-to-market by contracting out noncore processes to smaller, less bureaucratic and lower overhead companies, which can accelerate lead times for production items and new product development.
- To focus on what you do best. Few companies, if any, can afford to have all the technical expertise they require under their direct control.

The development of decision scenarios, focus and outsourcing decisions, and the support of the operations strategy are necessary rigors to apply in the SPI determination process.

Kanban Stock Points

Where kanban controls production, the system requires stock points. They are often next to producing work centers. These stock points are frequently the only significant work in process (WIP). Large staging areas and WIP warehouses disappear with their elaborate tracking systems and the people who operate them. Shortages, miscounts, and concerns about inventory accuracy also disappear.

Point-of-Use Delivery

With lean strategies the traditional and adversarial vendor relationships move towards cooperation. With changes in attitude come changes in supplier deliveries, quality, and transactions. The supplier may require direct access to production areas. This bypasses the usual receiving, inspection, and warehouse functions.

JIT Material Handling

Conventional manufacturing moves large loads of material infrequently. JIT and world-class manufacturing (WCM) strategies require small loads of material with frequent or continuous movement. These movements are often more direct and require shorter distances. Therefore, handling systems change. Fork trucks and automatic guided vehicles give way to hand trucks and simple conveyors.

Reduced Space

Many lean features translate directly to reduced space. The dramatic inventory reductions that occur also reduce space. JIT/WCM/lean factories may often require only 40 to 50 percent of the space used by conventional layouts. At the macrolevel, layouts using lean principles achieve material handling reductions of 80 to 90 percent over conventional layouts. But the strategic gain is the reduction in factory throughput time, typically from days to hours or minutes. Lean layouts also support the efforts of total quality management.

COMPUTER AIDS IN FACILITIES PLANNING

Early attempts to use computer aids concentrated on programs to generate layouts. With academic fervor, programs were written that would theoretically reduce the facilities layout problem into a single solution that would isolate and identify the one correct solution. The one solution approach was also embraced by the practicing engineer, not only because of university training but also because of the engineer's difficulty in accepting ambiguity. Ironically the early programs concentrated on automated solutions for steps that had no one solution, and when layouts could be generated more efficiently by interactive graphic systems. The advent of personal computers (PCs) with word processing, spreadsheet, graphics, simulation, and computer-aided design (CAD) programs provided many tools that accelerated the facility design process.

The layout process steps described in this chapter benefit from the following computer aid steps:

- Kordanz-evaluated project ratings for selection
- Project management packages to generate project schedules by phase, resource, and task
- CAD software for space verification, accurate pickup of available space, aisle space, travel path distances, and transport work calculations for option evaluation
- Equipment template libraries
- Rapid generation of site, building, and floor layouts
- Kerns's column-spacing model [8]
- Kordanz layout and material-handling option evaluations
- Simulation programs for the design and proving of complex operation designs

Manual drafting boards and blueprints are almost nonexistent at most job sites. The current tool of choice is CAD software or suite on a networked PC producing the designs required by each group from an integrated single or cross-referenced drawing. "The design task is more flexible because it allows for easy amendments and variations, as well as storage and reuse of design components. It is more reliable because the system automatically ensures that the geometric and other calculations are accurate. Materials quantities and costs can also be accurately estimated by the software program and are updated as designs are changed" [9].

Whether the software selected is shareware, costing a few dollars, or a set of one of the more popular advanced packages costing a few thousand dollars, some features need to be present. In addition to drawing tools, the software should at the least include the ability to assign layers, distinguish blocks, and import and export Drawing Exchange Format (DXF) files. Many projects will require the coordination of several trades and subcontractors each requiring their own set of specialized information or designs. By incorporating this information on layers, customized output can be generated from an integrated source simply by turning off any layers having the features, fixtures, text, or equipment that is not required in the view. The American Institute of Architects (AIA) and other organizations have proposed standardized naming and nomenclature for layers.

Where layers help maintain consistency of information and document control, blocks are developed to maintain consistency of data and layout control. Blocks allow for the development, insertion, and placement of consistently drawn and sized areas. This can be any type of fixture, feature, equipment, or text. Many CAD packages contain some blocks for building fixtures (e.g., toilets, ranges, refrigerators), but blocks related to specialized equipment within the facility will have to be developed and incorporated into the block library.

Finally, the electronic age requires portability of information. Since there is no de facto standard for CAD drawings, the easiest method for exchange of information is through DXF files. Although it is not 100 percent compatible, most CAD packages can import from and export to this format.

It is now accepted by facilities planners that the complexities of layout plans require real-time *programming* with interactive graphics and other computer aids at all stages and phases of the design process. CAD stands for computer-*aided design* not computer-*generated solutions.* Sly et al. [10] states it well: "As global competition creates a demand for leaner and more flexible factories, factory designers must be quicker at developing more and improved layouts. To meet this challenge, factory layout and design software needs to consider more issues, perform equally well with existing or new facilities, and prepare the quality and breadth of graphical and economic justifications expected by management."

CONCLUSION

World-class manufacturing and just-in-time concepts are simple enough. Execution, however, can be very difficult. This is particularly true for organizations that have evolved along functional lines.

The procedures presented in this chapter provide a range of structured approaches to help with the design of just-in-time/world-class/lean operating facilities. The focus algorithm identifies opportunities for focused factories at the site and building level, as well as at the plant and work cell level. The generic project plan structures the macro layout process at the plant level. Strategic facilities planning is a practitioner's art. Enhancement of the process evolves from day-to-day practice, and there is not just one way of practicing it. The procedure is sound, but the distinctive output depends on the quality of the practitioner and the climate in which he or she works. It can be difficult indeed for the practitioner and/or the organization to overcome the narrow myopic mental models that make it hard to visualize the competitive advantages available. But the infusion of fresh outside signals can broaden and enhance the vision of the future.

Extraordinary distinctive competitive advantages can result from effective, innovative lean facilities design. But the facilities design practitioner cannot do this alone. These advantages will result from the organization's business idea that the facilities layout design practitioner cooperatively translates into a strategic support operation.

APPENDIX: MANUFACTURING STRATEGY GUIDE SHEET

1. Site Mission
    - Site focus
        - Products
        - Markets
        - Volumes
        - Geography
    - Multisite integration
        - How does this site fit with others
    - Key manufacturing task
    - External strategic issues
        - Political
        - Environmental
        - Community involvement
        - Other
2. Process
    - Production mode(s)
        - Project
        - Functional
        - Cellular
        - Toyota
        - Line
        - Continuous
    - Process scale
        - Large—high capital
        - High volume
        - Long changeover
        - Large lots
        - Inflexible
        - Low direct cost
    - Setup/lot size
    - Capacity
        - Timing
        - Lead/track/lag
        - Reserve
    - Quality capability
    - Technology level
3. Nonphysical Infrastructure

FACILITIES LAYOUT AND DESIGN

- Quality approach
  - Quality policy
  - Quality at source
- Personnel policies
  - Technical skill depth
  - Technical skill breadth
  - Interpersonal skills
  - Employment security
  - Compensation
  - Training
  - Performance measurement
  - Safety
  - Ethics
  - Organization structure
- Organization focus
  - (Functional/product/other)
  - Depth
- Organization style
  - Exploitive
  - Bureaucratic
  - Consultative
  - Participative
- Accounting policies
  - Process/job costing
  - Time-based accounting
  - Overhead allocation
  - Decision criteria
  - Knowledge-base investments
  - Inventory accounting
- Production control
  - Trigger
    - Make to order
    - Make to stock
    - Kanban
  - Type
    - Physical link
    - Broadcast
    - Kanban
    - MRP
    - Reorder point
- Supplier policies
  - Selection criteria
  - Single/multiple sources
  - Contract time horizons
  - Scheduling approach
  - Shipping policies

4. **Facilities (physical infrastructure)**
   - Site focus
     - Product
     - Process
     - Market
     - Geographic
     - Other
   - Site location and size
   - Transportation access
   - Utility systems
   - Expansion policies
   - New product/process flexibility
   - Resale/disposal policy
   - Hazardous waste policy
   - Environmental issues

(*Courtesy of The Leawood Group 93204.*)

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BIOGRAPHY

William Wrennall, C. Chem, MRIC, CMC, is president of The Leawood Group Ltd., a management consulting firm based in Leawood, Kansas. His consulting career has included projects worldwide. During World War II he served in the British Army in Europe, India, and the Far East. He has held positions in industry as head of work study and training, and plant and general manager. He holds a B.Sc. from the University of Durham and an M.A. from Macquarie University in Australia. While in Australia, Wrennall was a lecturer in Operations and General Management. He is past president and a member of the advisory board of The World Confederation of Productivity Science and a Foundation Fellow of The World Academy of Productivity Science.

CHAPTER 8.3

A PARTICIPATORY APPROACH TO COMPUTER-AIDED WORKPLACE DESIGN

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Planning and designing new workplaces are complex processes; this is mainly due to the huge amount of information and knowledge, both technical and worker-related, that has to be taken into account. This chapter describes some useful tools and methods for improving the success of this process and discusses ways that CAD tools and virtual reality can be used (along with their advantages and possible shortcomings). Examples of different kinds of usable computer graphics software for workplace design are given and the use of virtual humans in virtual environments is described.

Planning and designing new workplaces is a process of change, and in order to achieve good solutions in a short time, it is essential to involve workers and other key persons in the company (i.e., to use a participatory approach). The use of participatory ergonomics is described, followed by one case study from Swedish industry in which the aforementioned methods and tools have been used. Finally, some future aspects of visualization and virtual humans are discussed.

BACKGROUND

When dealing with workplace design, the practitioner faces a huge amount of data to take into consideration. When either planning completely new workplaces or developing and redesigning existing ones, it is necessary to acquire information and knowledge about important aspects such as the old and new production systems, planned ideas and actions, limitations and legislation, and the people and the organization expected to work in the new environment. During the preliminary planning and design process and after the new workplace has been built, everyone involved needs information about how the new process should work and how they should operate and function in this new environment.

Traditionally, workplace design is taken care of by engineers, who often hold higher positions within or outside the company. It often happens, due to time limits, that a project is carried out fast, which means that the people who will use the workplace have little opportunity to influence the result. Furthermore, the information about the plan is usually presented late in the project and by means of traditional two-dimensional drawings of building layouts. Since many people do not clearly comprehend how the resulting work spaces will actually appear by studying this type of drawing, it is difficult for many of those directly involved to exert much influence on the design process or the final result.

Although the traditional approach makes the design process relatively fast, it also carries the risk that undetected built-in problems can make the total costs much higher than should be necessary. Some of these difficulties arise during the construction phase of the new workplace, since not everyone really understands how it should work; another problem is a slow start to the implementation process due to resistance to change. In particular, sound ergonomic solutions are difficult to reach due to lack of engagement of individual operators. These types of problems, which often make the total project time longer and more expensive then planned, are probably rooted in the fact that the operators and others working closely with production do not readily accept the changes. One factor may be that they have not been able to contribute their experience and ideas to the solutions. They do not feel as if it is *their* solution.

One way to improve the workplace design process is to adopt the participatory approach, in which the employees involved actively participate in the entire planning and design process. Several computer visualization programs are now available that make possible advanced three-dimensional drawings of a workplace. These programs are excellent tools for planning and designing workplaces. A discussion ensues about the use of three-dimensional computerized visualization tools and their role in the development of new workplaces using a participatory approach. Suggestions are made for achieving greater success in the evolution of ergonomic intervention.

WORKPLACE DESIGN

Workplace design consists of everything from the planning and design of a single workstation to a complete workshop or plant. Many different kinds of information and knowledge have to be taken into consideration before a picture of the situation, often complex, is complete. Just a few of the many factors that have to be taken into account are production technology; materials used in processes; flow of materials and products; routes of carriers and employees; product information such as weight, dimensions, and position; organization and competence level of personnel; and use of work aid equipment. Checklists are recommended for keeping track of the many details that form a complex whole.

In workplace design and development, four conditions must be dealt with in order to reach a good result:

1. The project must be fully supported at the management level.
2. As a start, it is important to form a small project group; care should be taken to ensure that this project group consists of persons with different backgrounds, including, for example, production engineering, workplace design, ergonomics, and manufacturing experience. Group members can be either internal employees or outside consultants.
3. Operators, well initiated in the work process, must be a part of the project group and take part in the planning; this is basic to the participatory approach. For the best possible results, these persons should be dedicated and have constructive ideas.
4. All involved have an opportunity to understand discussions and plans and to influence the results. One way to achieve this is to use special tools for visualizing solutions (e.g., computer graphic 3D representation), which can enhance participation.

Meeting these four conditions saves time and money. Emphasis is put on planning and participation. Even though the *planning* phase of the new workplace could consume more time and money, using the preceding methods will save costs in the end. When all interested parties agree on a solution, long-term costs are reduced and the project can be completed in a reasonably short time. Since everyone understands why the new workplace is designed as it is, the facility may be completed quickly and have the potential to start the new production rapidly. Hackman and Oldham [1] demonstrate that the time between the start of planning and final construction can be shortened and, in particular, that project money can be saved by using the participatory approach.

It is well known that the cost of making changes rises dramatically when production is started before all of the problems have been identified. By then, the problems are already built into the production process and are difficult to solve, according to Örtengren [2].

An advantage of having external members in the project group is that, besides offering broad knowledge to help develop solutions, they can also assist the company during the change process. These external group members, serving as change agents, should be able to bring not only new ideas to the organization, but also new implementation skills and perspectives. The group members should also be able to facilitate overcoming implementation problems that arise from resistance to change [3].

If the workers become involved early and remain involved throughout the whole change process, the chances of a successful project are increased. Including workers in the project group should avoid the “expert solution” (i.e., one without any input from the operators) [1]. Through the participatory approach, workers are able to put their ideas into the project and thus will be more positive to their new workplace. Knowing why things are planned as they are increases their understanding about the process and about the final result. Pikaar [4] discusses these issues. He states that an experienced operator can offer valuable contributions, as he or she possesses important detailed knowledge about the production process that is not documented or known by the rest of the employees. A problem, however, is to find suitable ways of involving the workers in the process. Pikaar believes that often the biggest problem is selling the idea of user participation to managers and designers.

The use of computer-aided design (CAD) and other computerized visualizing tools is essential. Groover [5] states that, “Computer aided design can be described as any activity that involves the use of the computer to create or modify an engineering design.” This means that CAD can be used in many different ways and at different levels of complexity. Groover also describes some of the advantages of CAD:

1. The designer’s productivity is increased.
2. Improved quality of the design is enabled, since a CAD system allows the designer to evaluate a number of alternative solutions.
3. Improved communications are a benefit, whether between the members of the design team or between it and other functions or the client.
4. A database for manufacturing is produced. The design of a system using a computer automatically generates data that can be used in the manufacturing and/or test stages of system development.

Furthermore Fallon and Dillon [6] note that to be able to increase human input to the design process, there is an increasing need for computer-based tools and methods. One of the reasons mentioned is that, given the general shortage of experienced human factors practitioners, the designers need supplementary tools that allow them to put human factors into the design process. Due to the multidisciplinary nature of design work, there is an increasing need to communicate at an operational level with other disciplines.

However, computerized visualization tools cannot always completely replace the building of mock-ups, which are structural models, or prototype workplaces that are tested and evaluated by technicians or workers. Computer visualization and animation of workplaces are often performed in the first phases of a project and the results are tested and verified in a mock-up.

CAD AND VIRTUAL REALITY

Visualization software is available in different degrees of complexity, from simple sketch software to virtual reality (VR) systems. In an advanced VR system the operator feels that he or she is in a virtual environment (VE) and that it is possible to move around and interact with the environment. Examples of PC-based CAD programs that can visualize objects and environments with different levels of complexity are ROOMER, Floorplan 3D, Drawfix Quick-CAD, and 3D-Studio. Examples of PC-based VR software are Superscape VR, Sense8, and VREAM. Advanced VR applications demand computers more powerful than PCs since the calculations and representations are very demanding, and Silicon Graphics workstations lead the market with their hardwired graphics engines and a specially developed graphics programming language. However, most software is for general purposes (e.g., MultiGen, which is a polygon editor for building the virtual environment, and Vega, which simulates your interaction with that virtual environment). Figure 8.3.1 shows the plan for a manual welding workstation developed with the CAD program ROOMER. Figure 8.3.2 shows a similar welding workstation created in 3D-Studio, which has more advanced features than ROOMER.

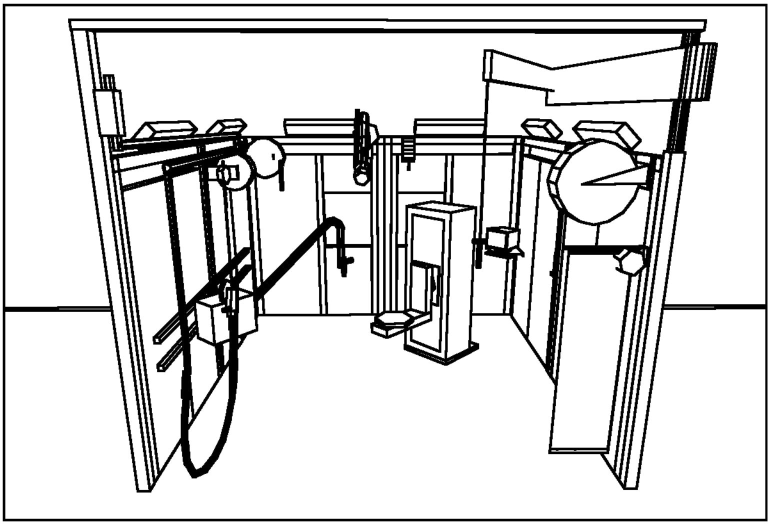

FIGURE 8.3.1 Plan for a manual welding workstation generated by the basic CAD program ROOMER.

According to Wilson, the term *virtual reality* describes something that is “real in effect although not in fact” (virtual) and that “can be considered capable of being considered fact for some purposes” (reality) [7]. To be called a *virtual reality system,* the system must be able to respond to user actions, have real-time 3D graphics, and give the user a sense of immersion. According to Pimentel and Teixeira [8], all three of these characteristics must be fulfilled. An immersive experience is so absorbing that the user does not notice the external surroundings. Current immersive systems stimulate users’ visual and aural senses in such a way that they feel immersed in the computer-generated experience.

Computer power is increasing rapidly, and software is becoming more advanced; this makes feasible the use of the Cave Automatic Virtual Environment (CAVE), which is a projection-

A PARTICIPATORY APPROACH TO COMPUTER-AIDED WORKPLACE DESIGN

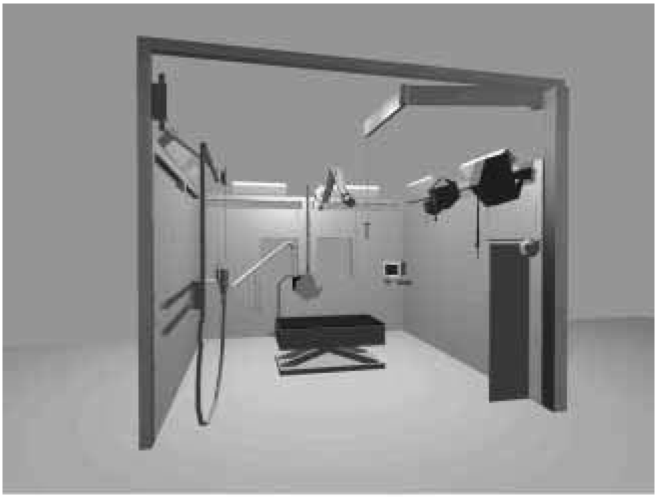

FIGURE 8.3.2 Welding workstation similar to the one shown in Fig. 8.3.1, created in the CAD program 3D-Studio, which has more advanced features than ROOMER.

based system that attracts great interest. The CAVE is currently the most sophisticated VR installation for scientific and artistic projects. It was developed in 1992 at the Electronic Visualization Laboratory of the University of Illinois. A Cave is a 3D environment that consists of a 3 × 3 × 3 meter (118 × 118 × 118 inch) room with three rear-projection screens for the walls and a down-projection screen for the floor. In the CAVE, all perspectives are calculated from the point of view of the user, and a head tracker provides information about the user's position. Instead of wearing the head-mounted display (HMD) often used in VR applications, viewers wear light LCD stereo shutter glasses, which alternately block the left and right eye. The computer generates two images, one for the left eye and one for the right eye. The computer system generates left and right eye images sequentially. An infrared signal, similar to that used for TV remotes, synchronizes the glasses to the computer images so that the right image is shown when the right lens is transparent and the left image is shown when the left lens is transparent. Images on the screen "move" with the viewers and surround them. A person wearing a handheld magnetic tracking device determines the direction and position of an image. Several persons can then, with the glasses, walk around in the room interacting with each other and with the virtual environment. For example, it is possible to physically walk around a nonexistent car projected into the room, to look inside it, and to make changes (e.g., to its color).

The acronym CAVE is also a reference to the essay "The Simile of the Cave" in Plato's *Republic,* in which the philosopher explores the ideas of perception, reality, and illusion. Plato used the analogy of persons facing the back of a cave and seeing shadows, on which they base their ideas of what is real.

VIRTUAL HUMANS: MANNEQUINS

Virtual humans, or mannequins, are computer models of humans. Mannequins are used for different purposes in both CAD and VR environments, and several different types of mannequins are available on the market.

The mannequin software has evolved from different fields of specialization: human factors engineering and ergonomics consulting firms (SAFEWORK and MQPro), robotics development (ROBCAD/Man and Deneb/ERGO), automotive and aerospace engineering (RAMSIS and MDHMS, or McDonnell Douglas Human Modeling System), university research (Transom Jack), and virtual reality software companies (dV/Manikin). All of these mannequins are, of course, different, and each one generally has its special intended use. For example, MDHMS is the mannequin most useful in cockpit and aircraft maintenance applications, whereas RAMSIS is very powerful in the design and testing of car interiors. ERGO-Man has characteristics suitable for visualization, animation, and simulation of, for example, manufacturing systems and materials handling. Some users in the industry have also developed their own versions of mannequins based on their specific needs. An ergo-nomic consulting company in Brazil has developed its own mannequin containing an anthropometric database of Brazilian people.

Figure 8.3.3 shows the mannequin ANTHROPOS working in a virtual environment. Figure 8.3.4 shows RAMSIS, developed for the automotive industry. Figure 8.3.5 shows Transom Jack performing a lifting task that afterward can be automatically evaluated from an ergonomic point of view.

Some of the more advanced mannequins can be used for tasks requiring motion and animation. Usually, the input to the mannequin environment is CAD geometry in various data formats (e.g., a part of a car or a workplace). The object that the mannequin is going to manipulate can also be built directly in the mannequin software. Then the mannequin is chosen and generated. The customized input of a special body shape is possible, along with input from a library of anthropometric data, to represent a single person, a subgroup of people, or a population from a specific part of the world. After the task or the movement the person shall perform has been programmed and the animation run, an ergonomic evaluation can be made. Outputs are ergonomic data such as joint forces and torque. Drawings of working positions, fields of reach, and visual fields are also common. Output can also consist of recorded data, including animation of walk paths and whole working sequences.

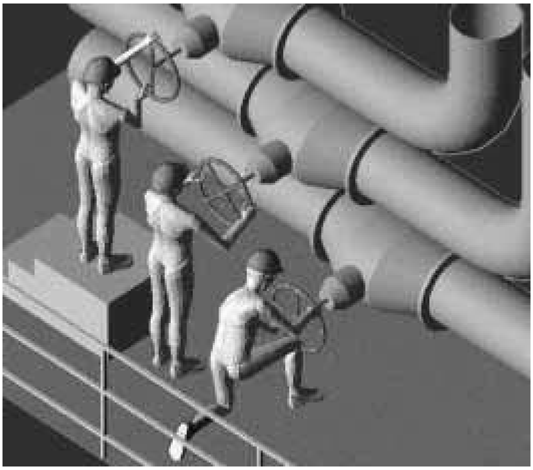

FIGURE 8.3.3 The mannequin ANTHROPOS working in a virtual environment. (Reprinted with permission from K. M. Lippman, IST-GmbH.)

A PARTICIPATORY APPROACH TO COMPUTER-AIDED WORKPLACE DESIGN

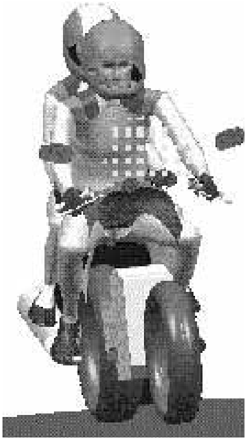

FIGURE 8.3.4 The RAMSIS mannequin, developed for the automotive industry. (Reprinted with permission from H. Rothaug, TECMATH GmbH.)

USING COMPUTERIZED VISUALIZATION IN WORKPLACE DESIGN

Working Procedures

Apart from a visualizing program to be used in the workplace design process, some procedures are beneficial to follow. As a start, to make a layout as accurate as desirable, specific data must be collected. This involves, for planning changes in an existing workplace, copying drawings of the building to obtain the exact measurements, measuring the geometry and position of existing machines and furniture, and taking photographs or making video recordings of equipment and people working. Also, questions have to be put to the operators to find out how they really perform their work and why. Supplementary data may need to be collected at a later stage. To save time and computer memory, it is advantageous to design different environments for different purposes (e.g., a nondetailed environment for displaying the overview of an entire workshop, making machines and furniture schematic and rough, and a more detailed environment for single workplaces). The overview layout is then used for discussions of such matters as materials flow, personnel and vehicles routes, and placements of different departments. Using the detailed layouts of the workplace, discussions can be held about working procedures, lifting heights, placement of equipment, and so on. When rendering views of a workplace, show the important parts of the workplace and the most important changes. Bird's-eye views are useful for discussions at the workshop level. For views of how the new workplace will look to someone inside it, do not set the camera view too high. For example, when the cam-

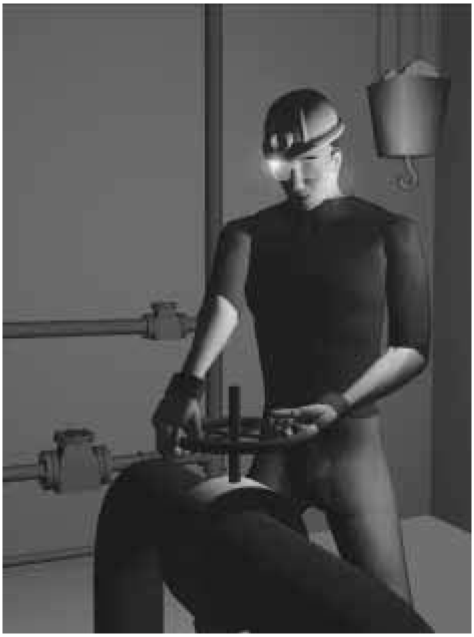

FIGURE 8.3.5 Transom Jack performing a lifting task, which will then be automatically evaluated from an ergonomic point of view. (Reprinted with permission from P. Tiernan, Transom Technologies, Inc.)

era represents the eye level of a normal person as 1.7 m (5 ft 6 in), it should be set slightly lower, to a height of approximately 1.5 m (4 ft 9 in) to give a realistic view.

Advantages and Disadvantages of Computerized Visualization

The choice of program does not affect the procedures, but it is critical for other reasons. The use of computer-aided visualization tools has many advantages. Using these tools to share ideas, suggestions, and results with the people affected by the project can make possible a clearer understanding of the process. Furthermore, the opportunity to involve and interest employees is increased. In comparison with traditional methods of visualizing layouts and solutions (e.g., two-dimensional paper sketches with glued-on icons of the machines or materials flow), the computer-based tools simplify making changes and trying different layouts, as described by Groover [5]. It is also possible to make changes directly in the CAD layout while involving workers on site at the workshop. This speeds up the planning process and enhances the participatory process. However, for this to be effective, the program used in this situation should not be too advanced, and the person designing and making the changes in the computer should be a skilled user of the software.

Possible drawbacks must also be mentioned. It is essential to use the most suitable type of visualizing tool in order to achieve a desirable result at a reasonable cost. If CAD tools or virtual reality software are too advanced, drawbacks include unnecessary cost and the possibility that 3D sketches could dampen creativity of the people involved. They may find the pictures to be so realistic and finished that ideas and comments are hampered. Because small companies rarely use advanced CAD programs for visualization, another possible negative aspect is the probability that an external expert will need to be hired simply to run the program. There is not yet adequate knowledge about how different levels of complexity in visualizing programs influence results in the workplace design process. Accordingly, future research should deal with questions such as: What software tools are appropriate in a given situation? Is the simple CAD software more suitable than virtual reality? Choices could be made with an eye to reducing project planning costs, increasing productivity, improving ergonomics, and enhancing understanding, participatory levels, and so on [9,10].

THE PARTICIPATORY ERGONOMICS APPROACH

Whether planning a single workstation or a whole production system, it is important to involve everyone affected by the changes and, in so doing, avoid the “expert solution,” whereby plans are formulated and presented by experts alone (from within and/or outside the company). If workers become involved early and remain involved throughout the entire design process, the chance of a successful project with better ergonomic solutions is increased. They have then been able to put *their* ideas into the project and they know *why* things are planned as they are. The participatory approach to the planning and design of a workplace is carried out by a small group of people from the company and internal or external experts. The company people possess special knowledge of their company and processes, and the experts represent specialized knowledge in such things as workplace design, ergonomics, and organization. It is very important to bring some operators into the project group, since they know the procedures of the daily work. (That is, the group should not be limited to supervisors, team managers, or production engineers.) The operators chosen should be dedicated and act as informal leaders of their teams. They should also have a positive attitude about the project and possible changes. When the group has been formed, it should then meet regularly throughout the project to discuss the problems, solutions, and new ideas that arise. To facilitate increased output with the participatory design process, computer-aided design tools for 3D drawings can be used to visualize solutions (3D drawings being easier to understand than the traditional 2D drawings).

Wilson and Haines [11] have identified six dimensions in which the participatory work can be defined: extent, focus, purpose, continuity, involvement, and application. These six dimensions can be a guide in the practical work done by a company. Briefly, the dimensions can be described as follows. *Extent,* from macroparticipation to microparticipation, applies to participants from management to single users. *Focus* refers to ergonomics at a macrolevel (applied to a whole organization) or at a microlevel (design of a single workplace). *Purpose* means implementing a complete change in an organization or achieving an effective implementation in an individual workplace. *Continuity* refers to whether participatory design is integrated as an everyday part of an organization's activities or applied only from time to time. *Involvement* indicates the level of participation—full and direct or representative. *Application* refers to whether a participant's views and ideas will be taken into consideration and applied directly (in person) or indirectly (by suggestion schemes).

THE CHANGE PROCESS

The aim of workplace design is to plan and implement new workplaces or to carry out specific improvements at existing workplaces. The result will be a change from the existing situation; this is likely to not only influence the appearance of the workplace and the equipment used, but also the definition and distribution of tasks, as well as the management structure and the organization. The reason is that every work process consists of subprocesses, specific machinery and tools, a number of actors at different hierarchical levels, and a structure for managing and controlling performance and output that are dependant on each other in a complex way. This means that a change anywhere in the process will cause concomitant changes in other parts. Thus, the work process can be described as an open system, the parts of which interact with each other and the environment. Applying systems theory when describing and analyzing the work process helps to clarify the inherent interdependencies and indicates how extensive primary and secondary changes must be to accomplish the intended result.

Ergonomic measures in a workplace always aim to create a better work situation for the employees as well as better performance and reduced resource consumption. This is done by adapting, in a general sense, the workplace and the organization to the employees' capabilities, needs, and limitations. When modern ergonomics was becoming established after World War II, the systems perspective was a central issue, and the term *ergonomics* was created to emphasize the integration of concepts from engineering, medicine, and psychology in the design of weapons systems. Despite this, many ergonomic changes have concentrated on individual workplaces, machines, or tools (i.e., applied at the microlevel). This has been so particularly in the effort to reduce what are known as *overload disorders* (back pain, neck and shoulder pain, epichondylitis, etc.), which most working people suffer from sooner or later. According to Hendrick [12], this narrow perspective is the reason that so many ergonomic measures have failed to improve the overall system productivity, worker health, and fundamental motivational aspects of work systems. Hendrick [13] identifies three major causes of the shortcomings of traditional (micro) ergonomics: (1) technology-centered ergonomics, in which the ergonomic contribution is made in relation to already designed hardware and software and whose influence therefore can only minimize problems to improve physical comfort; (2) a leftover approach, in which the main emphasis is on the technical aspects of the system design, implying that whatever the machine cannot do is left to the person who operates, maintains, and services the machine; (3) failure to integrate sociotechnical issues, meaning that the organization and work system are designed without taking into account personnel factors, organizational structure, or the external environment.

In response to the shortcomings of traditional microergonomic design, the field of macroergonomics has emerged as a result of influences from organizational psychology, organizational theories, the growing importance of psychosocial factors at work, and systems theory. The emergence of macroergonomics can be described as a logical consequence and acceptance of the increasing complexity of today's work environment. (For a detailed survey of this development, see Ingelgård [3].) Since ergonomic issues are vital in workplace design, this development has had a strong influence on methods and procedures for workplace design. Other influences come from industry's experience of change processes, particularly those in which a participatory approach has been applied.

The change process can vary, depending on the level from which it is initiated. In a top-down process, the management at a higher level has initiated and set the goal for the process. External consultants who analyze the problem at hand and suggest solutions based on their external experiences often carry out the planning and implementation. This often leads to resistance among the employees, high costs for education and training, and long implementation times. In a bottom-up process, on the other hand, the identification of a problem and the initiative to solve it come from those who are actually carrying out the operations. Often the solutions are developed and the implementation is performed using a participatory approach, which means that those actually impacted by the problem, together with managers and internal or external experts, participate in the solution. In this way, learning can even start during the development phase, and because people feel that they can influence the process, they are more positive and willing to accept the changes. However, even in a bottom-up process it is important for the success of the final result to have a firm support from top management.

A participatory approach has become more crucial in the product development of manufacturing industries as a result of the demand for shorter and shorter development times. Traditionally, the different stages of design and production preparations have been carried out sequentially. Nowadays, more and more activities must be conducted in parallel, in what is known as *simultaneous engineering,* which means that product planners, designers, production engineers, and workers collaborate in product development teams. The demand for effective exchange of information necessitates that the team members work with computers interconnected by a network so that they can have access to a common database that stores all information concerning the new product—drawings and pictures as well as data. The short development times also lead to fewer mock-ups and prototypes. Therefore the assessments of product style and function, as well as different aspects of the production conditions, are based on computer models and simulations. For these things, a large rationalization effect is expected, and extensive ongoing development will result in many more computer programs of varying degrees of sophistication. Examples of programs for the development of computer graphics workplace models are given elsewhere in this chapter.

APPLICATION EXAMPLE: DAROS, INC.

An intervention project was carried out at a Swedish company using computer-aided workplace design and a participatory approach. A project group was formed to ensure a participatory approach. It consisted of external researchers and personnel from the company working in the specific workplace. During the case study, two computerized visualization programs were used: a basic CAD program for three-dimensional layouts and a program visualizing and evaluating virtual humans and their working positions.

Introduction

A mechanical manufacturing company in Göteborg, Sweden, initiated the project. The company, DAROS Inc., has 130 employees and produces piston rings for large marine engines in ferries and tankers. The production process requires advanced knowledge of metallurgy, as the company casts its own blanks. The processes include casting, milling, grinding, blasting, and spraying the rings to produce an end product. The products are rings with dimensions

A PARTICIPATORY APPROACH TO COMPUTER-AIDED WORKPLACE DESIGN

from 400 to 1200 mm and weights of up to 11 kg. The project dealt with the ergonomic conditions at a particular workplace (Fig. 8.3.6), where the rings are blasted and plasma-sprayed in two different machines to be given a hard outer surface for durability to the temperatures and wear in the cylinder housing of the engines. Three men worked with these operations. In this particular project, not only a suggested solution was wanted, but also a complete intervention.

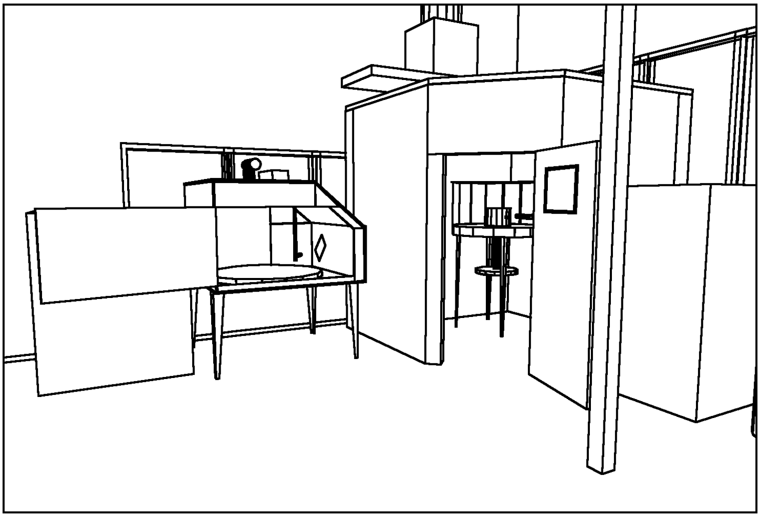

FIGURE 8.3.6 CAD drawing of the old workplace with the blasting machine on the left. Since the workplace layout permitted only minor changes to be made, CAD was used at the beginning of the project to facilitate the initial discussions, as well as for later design work when it is normally used.

Methods

Initially, an external group, consisting of three researchers from Lindholmen Development with knowledge of ergonomics and production engineering, met with the production manager and the three employees working at the specific workplace. The workers participating in the group were chosen by the production manager. The reason for forming such a group was to ensure a participatory approach. The group discussed the different ergonomic problems and related technical aspects. Directly after this first meeting, the workplace was visited and the group continued to discuss the problems, possible solutions, and various technical aspects. During the two-hour visit, the main task for one person of the external group was to collect data about the workplace and the equipment (construction drawings of the building, dimensions and make of equipment, its location in the room, etc.). This person also took photographs of the environment and equipment. A second person interviewed the operators and took photographs of the operators performing different tasks.

After the first visit, the external group continued to work with the ideas that had come up during the discussions. After a couple of weeks, they returned to further discuss a couple of potential solutions with the operators. After the whole group reached an agreement to proceed with one of the solutions, a final layout was made, a report was written, and the changing of the workplace was started. To quickly reach a solution that would be effective, close contacts were maintained with manufacturers that could provide needed equipment.

During the whole process, which lasted for about two weeks, the different ideas and solutions were continuously illustrated with ROOMER, a basic CAD program, which was intended to involve the end users and increase the understanding for the solutions of everyone involved in the project. It was hoped that the increased understanding would apply to the whole complex picture of the change project and also to single functional aspects of solutions.

Results

In the old workplace, the rings were handled entirely by hand. Altogether, each ring was lifted three times, often entailing awkward body positions. Several stages of the process required body positions producing high musculoskeletal load. At both the blasting machine and the plasma-spraying machine, time had to be spent positioning and adjusting the ring. The design of the machines did not allow proper body positioning. These things, along with a restriction against touching the inner side of the ring with hands or with any object, caused ergonomic problems to occur. The blasting machine operator had to bend forward with arms extended while holding the ring (Fig. 8.3.7). This caused great moment-of-force stress on the lower back. The weight of the ring, 10.5 kg (23 lb), generated a low back compression force of above 3000 N. This was estimated by means of the 3-Dimensional Static Strength Prediction Program, 3DSSPP [14], a program for ergonomic evaluation. Heavy load on the hipbone also occurred when the heaviest rings were handled.

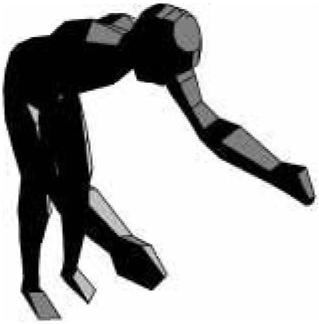

FIGURE 8.3.7 The body position at the old workplace when positioning the piston ring inside the blasting machine (see Fig. 8.3.6), as created with 3DSSPP software, which also generates data about forces and moments of force on the back and joints.

Figure 8.3.6 shows a CAD drawing of the old workplace with the blasting machine on the left. Since the workplace layout permitted only minor changes to be made, CAD was used to facilitate the initial discussions as well as for later design work when it is normally used. Figure 8.3.7 shows the body position at the old workplace when positioning the piston ring inside the blasting machine, as generated by 3DSSPP software, which includes data about forces and moments of force on the back and joints.

In the new workplace, which has now been built and is in use, the layout and functions eliminate the strenuous working positions that carried a risk of damage to muscles and ligaments. The task of manually lifting the bigger rings was changed to keep the forces on the extremities at acceptable risk levels. At the same time, the variation of the work has been preserved, which itself helps to prevent problems in the extremities.

The rings are fed from a pallet standing on a lifting table and moved easily by hand on a gliding surface to the first machine on the left, the blasting machine (Fig. 8.3.8). This machine has been rotated 180° and a new opening has been made in one wall of the machine. The working cell, where the next machine, the plasma-spraying machine, is still placed, has been extended and an opening has been made in the wall toward the new opening in the blasting machine. This working cell protects the surrounding environment from noise and pollution. A unique new lifting device that follows the movements of the hand has been installed, together with a proper magnetic gripping tool. The lifting device is used to pick up rings from the blasting machine, move them directly to the spraying machine, and lift them down to the pallet when finished.

In summary, the project ran smoothly and was fully supported by management. The solution, reached by consensus, was accomplished in a short time. As mentioned earlier, a project must have the full support of management, and one reason this project succeeded was that it was initiated by the president and run by the production manager. The technical and

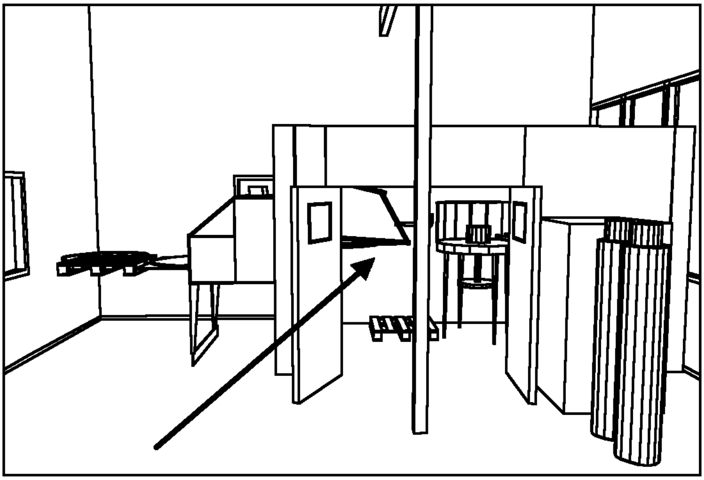

FIGURE 8.3.8 The new workplace redesigned in cooperation with the operators. At the start of the process, the rings are easily moved on a gliding surface into the first machine to the left, the blasting machine. Inside the working cell, the lifting device is pointed outward, easily following an operator's hand movements. It moves the ring to the plasma-spraying machine to the right in the working cell and down to the pallet when finished.

ergonomic solutions reached were of high quality and were completely accepted by both operators and management. The participatory approach made it possible to integrate the knowledge of the workers and to execute the changes easily and quickly due to the consensus of the participants. The CAD tools made it easy for everyone to understand each other because different solutions could be illustrated quickly during the process. The operators found that the basic CAD programs were helpful in showing the planned workplace with its new functions and ergonomic aspects.

In this project, the external group of experts fulfilled several of the functions described earlier in the chapter. They made contributions from a broad range of knowledge when working out the solutions, assisted the company during the change, and also acted as a change agent; thus they were able to bring new ideas, new implementation skills, and new perspectives to the organization [1,3].

The definitions of Wilson and Haines [11], discussed earlier in the chapter, can be used to describe the participatory work in this project:

Extent was of the type macroparticipation, as both the production manager and the president were involved.

Focus took the form of ergonomics at a microlevel, since a single workplace was designed.

Purpose was defined as reaching an effective implementation of a specific workplace.

Continuity, at this stage, was time-specific. However, the long-term goal was to influence the whole company to use the participatory approach in daily work.

Involvement took the form of partial direct involvement, as there was only one small group.

Application was of the direct kind in the adoption of participants' views and ideas.

FUTURE TRENDS

Advanced Virtual Reality Workplace Design

As Wilson [7] notes, "VR/VE has the potential to support many types of ergonomics contributions, including assessments of workplace layouts giving egocentric viewpoints for testing consequences for reach and access, reconfiguring and testing alternative interface designs, checking operation and emergency procedures, training for industrial and commercial tasks, and teaching in special needs or general sectors." In the future, the CAVE system and related techniques should enable the assessment of virtual workplaces and products in a more advanced way than the CAD and VR of today. In the CAVE, a person can actually interact with other humans or with virtual humans in the same virtual workplace. In a CAVE system at Chalmers University of Technology in Göteborg, Sweden, different applications in workplace design and virtual humans are being investigated and developed.

Intelligent Virtual Humans Trying Out Virtual Workplaces and Products

Neural networks (NNs) may be described in the literature as *artificial neural networks* (ANNs), among other names. Neural networks are so named because they are based on the neural structure of the human brain, both having many highly interconnected neurons. The NNs learn by making decisions and predictions from previously stored knowledge. NNs can be used to add capabilities to computer systems. The function of NNs is to mimic what the brain does best: associate reasoning, learning, and thought. In NNs, information is stored as patterns, not as a series of information bits as in normal computers, and just as one cannot look into the brain and extract its knowledge, the designers of NNs cannot simply look at the neurons and see what is stored there. NNs are not an evolution of normal serial computers. Their architecture, function, and use differ fundamentally from those of conventional computers. NNs are more like computing memories whose operations are based on associate reasoning [15].

As part of an ongoing European research project called ANNIE—Application of Neural Networks to Integrated Ergonomics—we are developing a computer tool for the design of efficient and ergonomically safe workplaces.

An artificial neural network, after training, will be able to predict movements and control a virtual human (mannequin) to perform in a CAD or virtual reality model of the environment to be tested. The training of the neural network is based on the collection of real human data by a system that captures specific human motions. Ergonomic assessment methods are used to describe the computer mannequin's movements. The system will be made compatible with some of the different mannequins on the market. Participants from Sweden, Italy, and Germany include several universities and companies from the motor, space, and manufacturing industries. The final software system will be tested and used for future vehicle models, space stations in orbit, and manufacturing workplaces. In Sweden, participants are the Swedish National Institute for Working Life and Chalmers University of Technology, partner to Lund University of Technology.

The advances described here apply to the field of the fidelity of virtual humans (to human movement, size, strength limits, etc.). Progress is also being made to improve both interactive and real-time applications, that is, temporal fidelity. So far, temporal fidelity has been mainly used for computer games, simulation (e.g., military battlefield simulation), and training (e.g., development of skill in medical operations). Efforts are also being made to design human models that optimize individual performance, intelligence, and even character. This would be particularly useful for the *agents* (virtual human figure representation controlled by computer programs) and *avatars* (controlled by a live person) used in games and virtual worlds on the Internet [16]. At present, and with an eye on the near future, all of these efforts aim to make

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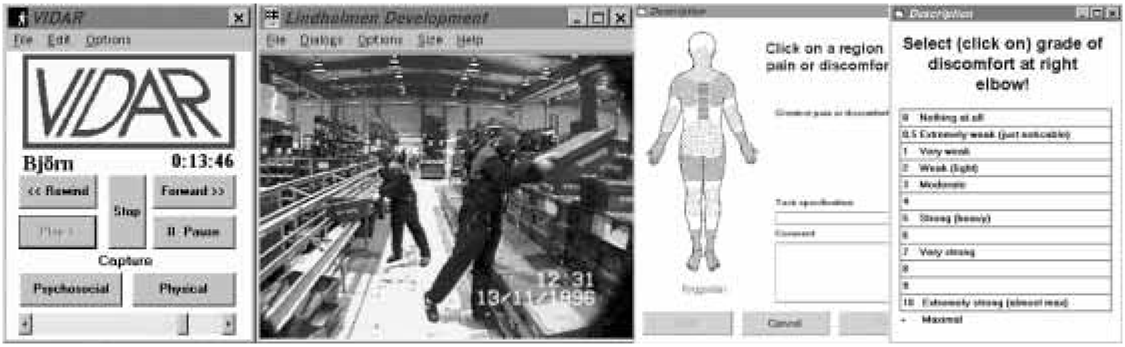
virtual humans as nearly human as possible—not only to look human, but to appear to be human and to act autonomously, with seemingly intelligent and self-generated decisions and actions. As these goals are advanced for military and entertainment purposes, they are also picked up and adapted for industrial applications.

New Tools for Integrating Ergonomic Knowledge into Workplace Design

To optimize human factors in the design process, Fallon and Dillon [6] point out that there will be an increasing need for computer-based tools and methods. Work is in progress to meet this need. In the extensive Swedish COPE program (Cooperative for Optimization of industrial production systems regarding Productivity and Ergonomics), the goal is to produce a practical toolkit in which several of the tools are computer-based [17]. The COPE program is carrying out several studies in cooperation with industrial partners on-site at industrial plants. All of the studies are organized as projects in which physical and organizational changes will be made and new workplace designs will be developed as a final result. The aim is to develop and refine tools that, after COPE is finished, can be used by practitioners in their daily work. The tools are intended to help in dealing with productivity and efficiency issues without worsening the ergonomic situation. Put another way, the tools should enable the design of sound ergonomic workplaces and simultaneously increase the productivity.

An example of a tool that has been further developed and applied in the COPE program is one called VIDAR [18]. It is computer software designed for assessing the ergonomic and psychosocial situation of operators at a specific workplace in a fast and easy way. First a video recording is made of a worker who is performing work. The recorded sequence is then played back on a PC visual display so that the work situation can be analyzed together with the worker. All work situations that induce pain or discomfort, as judged by the worker, are saved as photos in a file. The operator marks the location and degree of pain. Long video recordings may be reduced by saving only those situations causing problems. These data then form the basis for designing workplace changes to improve ergonomics.

In Fig. 8.3.9, the operator makes an ergonomic assessment of his or her own work while looking at a video display unit (VDU). Another application of the same technique, closely related to VIDAR, is under development. It is a computerized method for the combined analysis of electromyography (EMG), or measuring muscle activity, and video recordings of long work sequences. EMG is a well-known method used to investigate work sequences. By displaying two synchronized windows on the VDU showing EMG data and video recordings of the same work performed, ergonomic analysis can be improved [19]. In Fig. 8.3.10, a person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Description
0 Nothing at all
0.5 Extremely weak (just noticeable)
1 Very weak
2 Weak (light)
3 Moderate
4
5 Strong (heavy)
6
7 Very strong
8
9
10 Extremely strong (almost max)
• Maximal
Cancel

Click on a region pain or discomfor

Select (click on) grade of discomfort at right elbow!

FIGURE 8.3.9 VIDAR. The filmed operator makes an ergonomic assessment of his or her own work while looking at the video film on a video display unit (VDU).

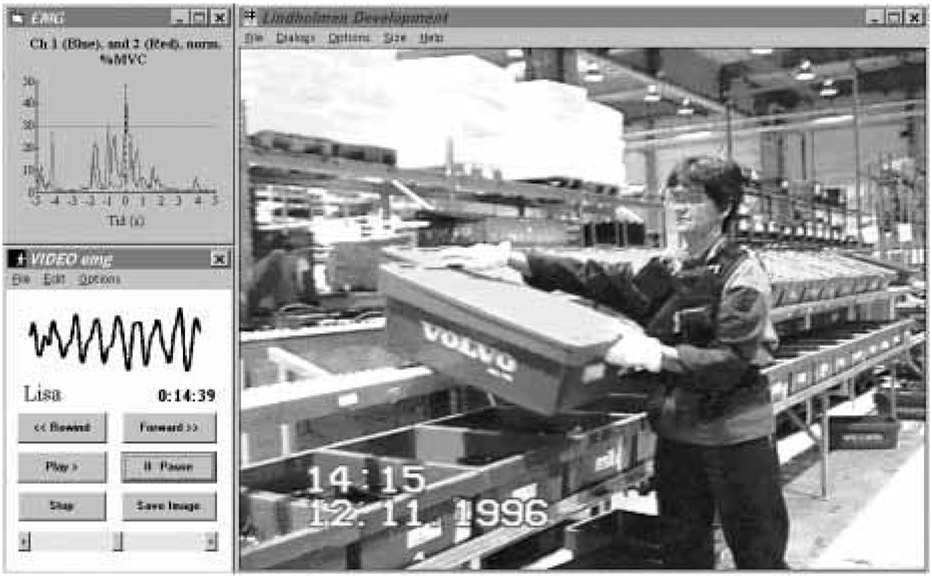
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FIGURE 8.3.10 A person carries the EMG equipment on the waist during the recorded sequence. Then the EMG recordings can be seen at the same time as the recorded sequence on the VDU.

carries the EMG equipment on the waist during the recorded sequence. Then the EMG recordings can be seen at the same time as the recorded sequence on the VDU.

ACKNOWLEDGMENTS

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BIOGRAPHIES

Anders Sundin, M.Sc. (mechanical engineering), held a position between 1992 and 1999 at Lindholmen Development, an independent research and development company in Göteborg, Sweden. He has worked as a consultant in the fields of computerized workplace design, industrial engineering, and ergonomics. He is a Ph.D. candidate at the Department of Human Factors Engineering, School of Mechanical and Vehicular Engineering, Chalmers University of Technology. Since 1995, Sundin has been a Certified European Ergonomist. Before 1992, he held a position at the Swedish Institute for Production Engineering Research (IVF). He is also a member of Work Group 33, Workplace Design, of the Swedish Welding Commission and a member of the executive group of the design engineering program at Hisingen Vux. In 2000, he was hired by the Swedish National Institute for Working Life.

Roland Örtengren has an M.Sc. degree in engineering physics and a Ph.D in applied and medical electronics, both from Chalmers University of Technology (CUT), Sweden, and he is a Certified European Ergonomist. Since 1990, Örtengren has been a professor of human factors engineering at the School of Mechanical and Vehicular Engineering at CUT. Before that, he was professor of industrial ergonomics for nine years in the Department of Mechanical Engineering, Linköping Institute of Technology, Sweden.

Örtengren teaches and conducts research in ergonomics and biomechanics. Current research interests include development of methods using 3D computer graphics for ergonomic design, evaluation of workplaces (including movement simulation), and development of new principles for design of materials handling chains in transportation and goods distribution (from a systems ergonomics perspective). Örtengren is author and coauthor of more than 250 papers, reports, and book chapters in biomechanics and ergonomics. He is a member of several professional societies.

CHAPTER 8.4

PLANNING A MANUFACTURING CELL

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This chapter explains step-by-step how to plan a manufacturing cell. It discusses the information and analyses required at each step and the outputs achieved. Several types of cells are discussed. Special issues related to automation are also discussed. A comprehensive checklist is provided covering all major aspects of cell planning and operation, including physical arrangement, operating procedures, organization, and training.

BACKGROUND

Definition of a Manufacturing Cell

A manufacturing cell consists of two or more operations, workstations, or machines dedicated to processing one or a limited number of parts or products. A cell has a defined working area and is scheduled, managed, and measured as a single unit of production facilities. Typically, a cell is relatively small, and may be virtually self-managed. Usually, the outputs of a cell are more or less complete parts or assemblies, ready for use by downstream operations, or for shipment to a customer.

Three aspects—physical, procedural, and personal—must be addressed when planning a manufacturing cell. Cells consist of *physical facilities* such as layout, material handling, machinery, and utilities. Cells also require *operating procedures* for quality, engineering, materials management, maintenance, and accounting. And because cells employ *personnel* in various jobs and capacities, they also require policies, organizational structure, leadership, and training.

A cell is essentially a production line (or layout by product) for a group or family of similar items. It is an alternative to layout and organization by process, in which materials typically move through successive departments of similar processes or operations. This layout by process generally leads to higher inventories as parts accumulate between departments, especially if larger batches or lots are produced. There is more material handling required to move parts between departments, and overall processing time is longer. Exposure to quality problems is greater, since more time may pass and more nonconforming parts may be produced before the downstream department notices a problem.

Benefits of Cells

The principal physical change made with a manufacturing cell is to reduce the distance between operations. In turn, this reduces material handling, cycle times, inventory, quality problems, and space requirements. Plants installing cells consistently report the following benefits when compared to process-oriented layouts and organizations:

- Reduced materials handling—67 to 90 percent reductions in distance traveled are not uncommon, since operations are adjacent within a dedicated area.
- Reduced inventory in process—50 to 90 percent reductions are common, since material is not waiting ahead of distant processing operations. Also, within the cell, smaller lots or single-piece flow is used, further reducing the amount of material in process.
- Shorter time in production—from days to hours or minutes, since parts and products can flow quickly between adjacent operations.

In addition to these primary, quantifiable benefits, companies using cells also report:

- Easier production control
- Greater operator productivity
- Quicker action on quality problems
- More effective training
- Better utilization of personnel
- Better handling of engineering changes

These secondary benefits result from the smaller, more focused nature of cellular operations.

Difficulties in Planning and Managing Cells

To obtain the benefits of cells, planners and managers often must overcome the following difficulties:

- Worker rejection or lack of acceptance—often due to lack of operator involvement in planning the cell or to insufficient motivation and explanation by management, especially if the outcome is perceived to be a workforce reduction.
- Lack of support or opposition by support staffs in production planning, inventory control and/or cost accounting—usually when creation of the cell causes changes in procedures and practices, or reduces the amount of detail reported from the plant floor.
- Reduced machine utilization—due to dedication of equipment to cells and to families of parts. In some cases, additional, duplicated machinery may be required.
- Need to train or retrain operators—often for a wider range of duties and responsibilities.
- Wage and performance measurement problems—especially when individual and piece-rate incentives are in use. The team-oriented nature of the typical cell, and the goals of inventory reduction, may work against traditional incentives and measures.

TYPES OF MANUFACTURING CELLS

Cells take different forms based on the characteristics of the parts (P) and quantities (Q) produced and the nature of the process sequence or routing (R) employed. The relationship of these characteristics—P, Q, and R—and their influence on manufacturing cells can be seen in Fig. 8.4.1

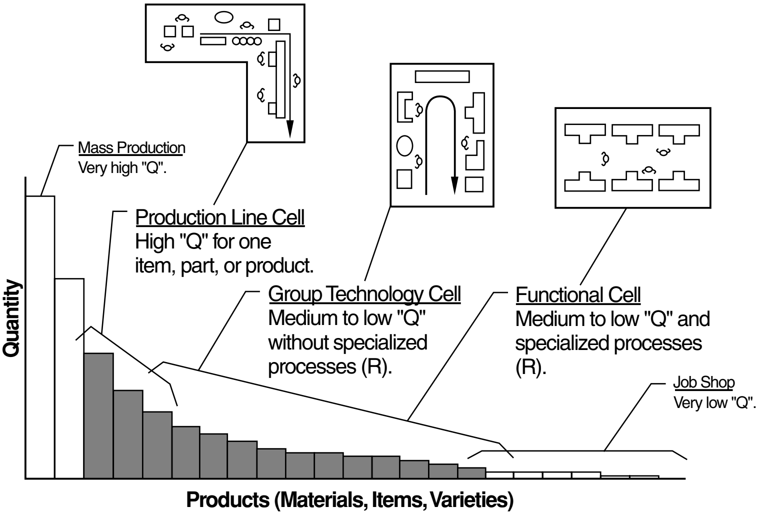


FIGURE 8.4.1 Key considerations and types of manufacturing cells. *(© 1999 Richard Muther & Associates.)*

Production Line, Group of Parts, and Functional Cells

Cells are typically used to serve the broad middle range of a product-quantity (P-Q) distribution. Very high quantities of a part or product lend themselves to dedicated mass production techniques such as high-speed automation, progressive assembly lines, or transfer machines. At the other extreme, very low quantities and intermittent production are insufficient to justify the dedicated resources of a cell. Items at this end of the P-Q curve are best produced in a general-purpose job shop. In between these quantity extremes are the many items, parts, or products that may be grouped or combined in some way to justify the formation of one or more manufacturing cells.

Within the middle range, a *production line cell* may be dedicated to one or few high-volume items. This type of cell will have many of the attributes of a traditional progressive line, but it is usually less mechanized or automated since volumes are still lower than those with the highest volumes.

Medium and lower production quantities are typically manufactured in *group technology* or *group-of-parts cells.* These are the most common types of cells. They exhibit progressive flow, but the variety of parts and the associated variety of routings works against a production line.

If operations are specialized in some way, requiring special machinery and utilities, or special enclosures of some kind, then a *functional cell* may be appropriate. Functional cells are often used for painting, plating, heat treating, specialized cleaning, and similar batch or environmentally sensitive operations. If the functional cell processes parts for other group-of-parts or production line cells, it will introduce extra handling, cycle time, and inventory since parts must be transported and held ahead of and behind the functional cell. For this reason, planners should first examine the practicality of decentralizing or duplicating the specialized process(es) into group-of-parts or production line cells.

The steps required to plan a manufacturing cell are the same for all three types of cells: production line, group technology, and functional. However, the emphasis and specific techniques used will vary somewhat based on the physical nature of the manufacturing processes involved. For example, when planning for machining and fabrication cells, the capacity of key machines is critical. The time required to change from one part or item to another is also critical. Allowances for setup and capacity losses due to changeovers are very important. Personnel planning may be of secondary importance, after the number of machines has been determined. In contrast, when planning for progressive assembly, the variability of operation times must be understood, and the work must be balanced among the operators to assure good utilization of labor. In such assembly cells, utilization of equipment may be a secondary issue.

HOW TO PLAN A MANUFACTURING CELL

Most cells can be planned using a simple six-step approach:

1. Orient the project
2. Classify the parts
3. Analyze the process
4. Couple into cell plans
5. Select the best plan
6. Detail and implement the plan

This approach is fully described in the booklet *Simplified Systematic Planning of Manufacturing Cells* by Richard Muther, William E. Fillmore, and Charles P. Rome [1]. A synopsis of this approach is presented here by permission of the authors.

Step 1. Orient the Project

The cell planner's first step is to organize the project, beginning with a statement of objectives, operational goals, and desired improvements. External conditions imposed by the facility or the surroundings should be noted. The planning or business situation is also reviewed and understood for issues such as urgency and timing, management constraints, or other policy matters. The scope of the project and the form of the final output are agreed to.

All cell-planning projects begin with a set of open issues. These are problems, opportunities, or simply questions that will affect the planning of the cell or its subsequent operation. These issues must be resolved and answered during the planning process. Typical issues include responsibilities for inspection and maintenance, cost accounting methods, scheduling procedures, job design, and training—in addition to physical issues related to available space, equipment, and utilities. The planner and the planning team should list their issues at the first opportunity and rate the relative importance of each to the project.

Orientation also requires an achievable project schedule, showing the necessary tasks and the individuals assigned to each. The essential planning tasks can be established using this six-step procedure, adapted to the specifics of the project at hand. The final output of step 1—Orient the Project—can be summarized on a simple worksheet or form like that shown in Fig. 8.4.2.

ORIENTATION & ISSUES WORKSHEET

Project Name *Oven Assembly Cell* **Project No.** *99509*
By *Team* **With** *DM*
Date *10/8* **Sheet** *1* **of** *1*

1. Objective(s): *Reduce materials handling; accomodate plant ordering procedures; minimize throughput time, attain desired output rate, no more, mo less.*

2. External Conditions: *Locate in old Receiving area. Moves of baskets and totes-on-pallets by fork truck.*

3. Situation: *Quick start up required to meet customer demand. Use available equipment.*

4. Scope and Form of Output: *Cell must start deliveries by 11/15.*

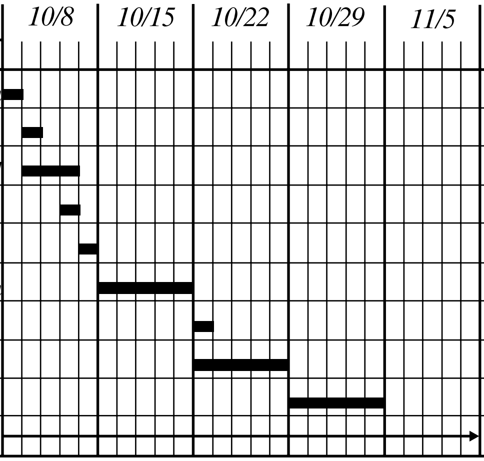
PLANNING ISSUES				Action to Resolve	Resp.	Proposed Resolution	√
1	*Will team be cross-trained?*	*I*					
2	*What will project life be?*	*E*					
3	*Can takt time goal be met?*	*A*					
4	*Must use avail. equipment*	*A*					
5	*Must start delivery by 11/15*	*A*					
6							
7							
8							
9							
10							

Dominance/Importance Rating ↑ ↑ Mark "X" if beyond control of company/plant/project

Notes:

Distribution *Team* By *Team* With *DM* Status as of

PROJECT SCHEDULE



No	Action Required	Who	Notes & Further Action
1	*Define & schedule project*	*Team*	
2	*Classify parts*	*BG*	
3	*Analyze & document process*	*PH*	
4	*Balance operations*	*PH*	
5	*Equipment & flow diagram*	*PH*	
6	*Develop cell plans*	*Team*	
7	*Evaluation meeting*	*All*	
8	*Make implementation plan*	*DM*	
9	*Install available equipment*	*DM*	
10	*Complete implementation*	*All*	*Target 11/15*

Notes:

FIGURE 8.4.2 Cell planning orientation and issues worksheet. *(© 1995 Richard Muther.)*

Step 2. Classify the Parts

Most projects have a candidate list of potential parts that could be made in the cell. These parts typically have the same or similar routings. The planner must still clarify and confirm that these candidate parts do belong in the cell, and identify those that do not. The planner must also classify the parts to simplify the analysis and design of the cell. The first cut at classification usually involves the physical characteristics of the candidate parts. These include

- Basic material type
- Quality level, tolerance, or finish
- Size
- Weight or density
- Shape
- Risk of damage

Additional common considerations for classification include

- Quantity or volume of demand
- Routing or process sequence (and any special or dominant considerations)
- Service or utility requirements (related to the process equipment required)
- Timing (may be demand-related, e.g., seasonality; schedule-related peaks or valleys; shift-related; or possibly related to processing time if some parts have very long or very short processing times)

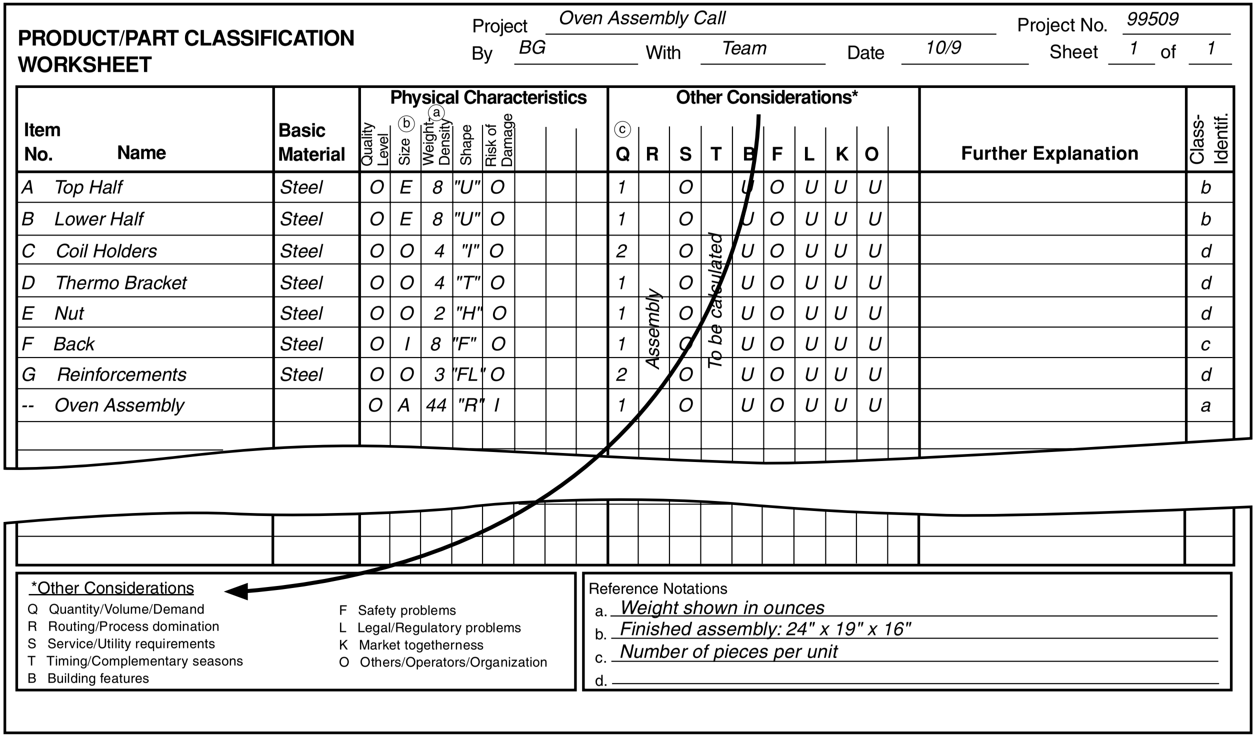
Less common but occasionally significant classification factors include building features, safety issues, regulatory considerations, marketing-related considerations, and even organizational factors that may be reflected in the way that a specific part is scheduled and produced.

All of these factors can be tied together into a worksheet like the one shown in Fig. 8.4.3. The planner identifies and records the physical characteristics and other considerations for each part or item. If it seems awkward to record each amount or specific dimension, one can rate the importance or significance of each characteristic as to its contrast or dissimilarity with the other parts. Use the vowel letter and the order-of-magnitude rating code illustrated in Fig. 8.4.3 and defined here:

A = abnormally great
E = especially significant
I = important
O = ordinary
U = unimportant

After recording or rating the physical characteristics and other considerations for each part or item, note those parts that have similar characteristics—that is, classify the parts according to the most important characteristics and considerations. Assign a class code letter to each class, group, or combination of meaningful similarities. Enter the appropriate class letter code for each part or item in the class identification column.

When a large number of different parts will be produced, planners should place special emphasis on sorting the parts into groups or subgroups with similar operational sequences or routings. Those assigned to a class will go through the same operations. Generally, for cells producing many parts, this is the most useful type of classification for the subsequent steps in cell planning. The final output of step 2—Classify the Parts—is a clear listing of the classes or groups of parts to be produced in the cell.



PRODUCT/PART CLASSIFICATION WORKSHEET

Project *Oven Assembly Call* Project No. *99509*
By *BG* With *Team* Date *10/9* Sheet *1* of *1*

Item No.	Name	Basic Material	Physical Characteristics: Quality Level	ⓑ Size	ⓐ Weight-Density	Shape	Risk of Damage			Other Considerations*: ⓒ Q	R	S	T	B	F	L	K	O		Further Explanation	Class-Identif.
A	*Top Half*	*Steel*	*O*	*E*	*8*	*"U"*	*O*			*1*		*O*		*U*	*O*	*U*	*U*	*U*			*b*
B	*Lower Half*	*Steel*	*O*	*E*	*8*	*"U"*	*O*			*1*		*O*		*U*	*O*	*U*	*U*	*U*			*b*
C	*Coil Holders*	*Steel*	*O*	*O*	*4*	*"I"*	*O*			*2*		*O*	*To be calculated*	*U*	*O*	*U*	*U*	*U*			*d*
D	*Thermo Bracket*	*Steel*	*O*	*O*	*4*	*"T"*	*O*			*1*	*Assembly*	*O*		*U*	*O*	*U*	*U*	*U*			*d*
E	*Nut*	*Steel*	*O*	*O*	*2*	*"H"*	*O*			*1*		*O*		*U*	*O*	*U*	*U*	*U*			*d*
F	*Back*	*Steel*	*O*	*I*	*8*	*"F"*	*O*			*1*		*O*		*U*	*O*	*U*	*U*	*U*			*c*
G	*Reinforcements*	*Steel*	*O*	*O*	*3*	*"FL"*	*O*			*2*		*O*		*U*	*O*	*U*	*U*	*U*			*d*
--	*Oven Assembly*		*O*	*A*	*44*	*"R"*	*I*			*1*		*O*		*U*	*O*	*U*	*U*	*U*			*a*

*Other Considerations
Q Quantity/Volume/Demand
R Routing/Process domination
S Service/Utility requirements
T Timing/Complementary seasons
B Building features
F Safety problems
L Legal/Regulatory problems
K Market togetherness
O Others/Operators/Organization

Reference Notations
a. *Weight shown in ounces*
b. *Finished assembly: 24" x 19" x 16"*
c. *Number of pieces per unit*
d.

FIGURE 8.4.3 Product/part classification worksheet. *(© 1995 Richard Muther.)*

PLANNING A MANUFACTURING CELL

Step 3. Analyze the Process

In step 3, the planner uses charts and diagrams to visualize the routings for each class or subgroup of parts, and then calculates the numbers of machines and/or operators and workplaces that will be required to satisfy the target production rates and quantities.

If the plan is for an assembly cell, the preferred way to visualize the process is with an operation process chart like that shown in Fig. 8.4.4. In addition to showing the progressive assembly of the finished item, this chart also shows the labor time at each step. Given a target production rate and the number of working hours available, the planner calculates the work content of the process and breaks it into meaningful work assignments. In this way, the required number of operators and workplaces is determined, along with the flow of materials between them. Assumptions or calculations must be made to establish the time that will be lost to non-value-adding tasks such as material handling, housekeeping, and the like. The formal name for this process is *line balancing.* A good line balance achieves the desired production rate with the minimum number of operators and minimal idle time.

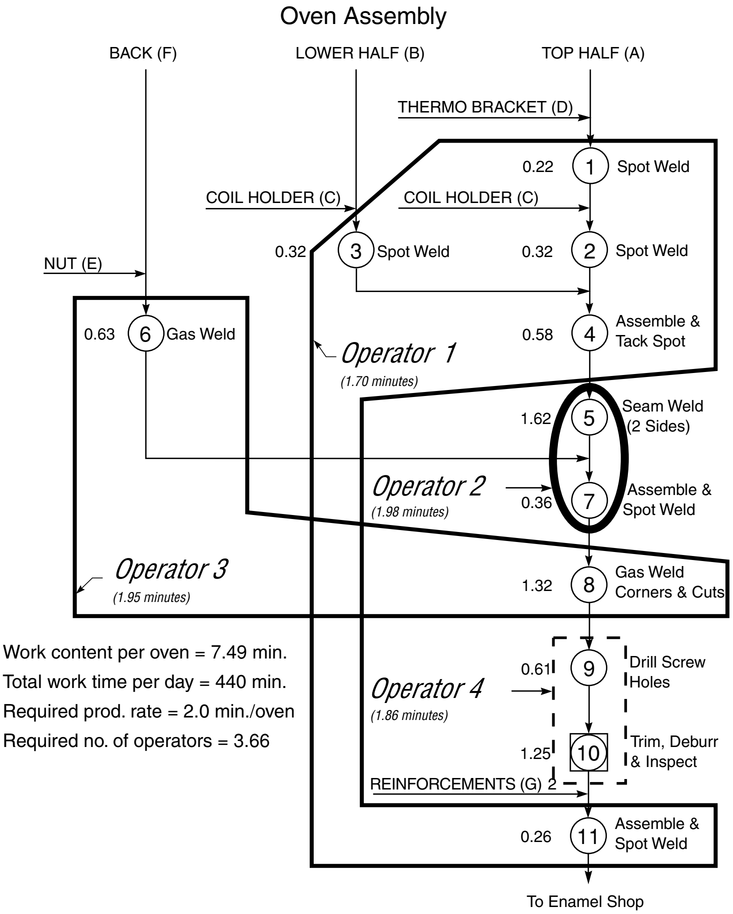

Oven Assembly
BACK (F)
LOWER HALF (B)
TOP HALF (A)
THERMO BRACKET (D)
0.22
1
Spot Weld
COIL HOLDER (C)
COIL HOLDER (C)
0.32
3
Spot Weld
0.32
2
Spot Weld
NUT (E)
0.63
6
Gas Weld
0.58
4
Assemble & Tack Spot
Operator 1
(1.70 minutes)
1.62
5
Seam Weld (2 Sides)
Operator 2
(1.98 minutes)
0.36
7
Assemble & Spot Weld
Operator 3
(1.95 minutes)
1.32
8
Gas Weld Corners & Cuts
Work content per oven = 7.49 min.
Total work time per day = 440 min.
Required prod. rate = 2.0 min./oven
Required no. of operators = 3.66
0.61
9
Drill Screw Holes
Operator 4
(1.86 minutes)
1.25
10
Trim, Deburr & Inspect
REINFORCEMENTS (G) 2
0.26
11
Assemble & Spot Weld
To Enamel Shop

FIGURE 8.4.4 Operation process chart. *(© Richard Muther & Associates.)*

PLANNING A MANUFACTURING CELL

Once balanced to the planning team's satisfaction, workplaces and equipment are defined and represented in an equipment and flow diagram. This is the final output of step 3 (see Fig. 8.4.5). In this example, scaled templates represent the equipment. Such graphic detail is useful but not mandatory. A simple square symbol can be used to represent each operator workstation, or each machine. Numbers of lines and lowercase letters designate the flow of parts and materials.

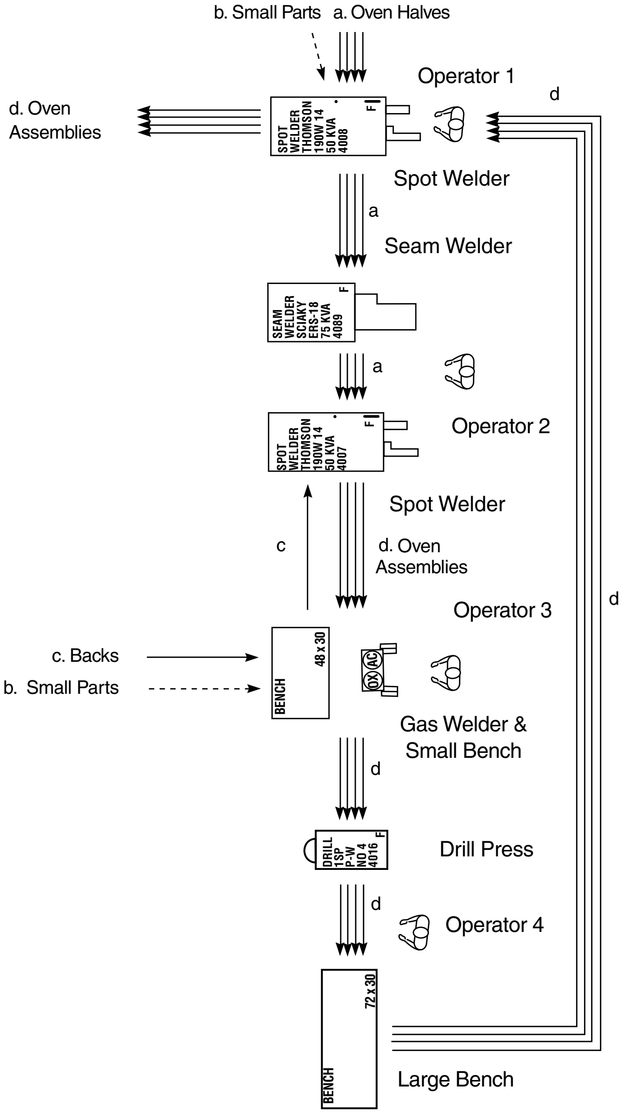
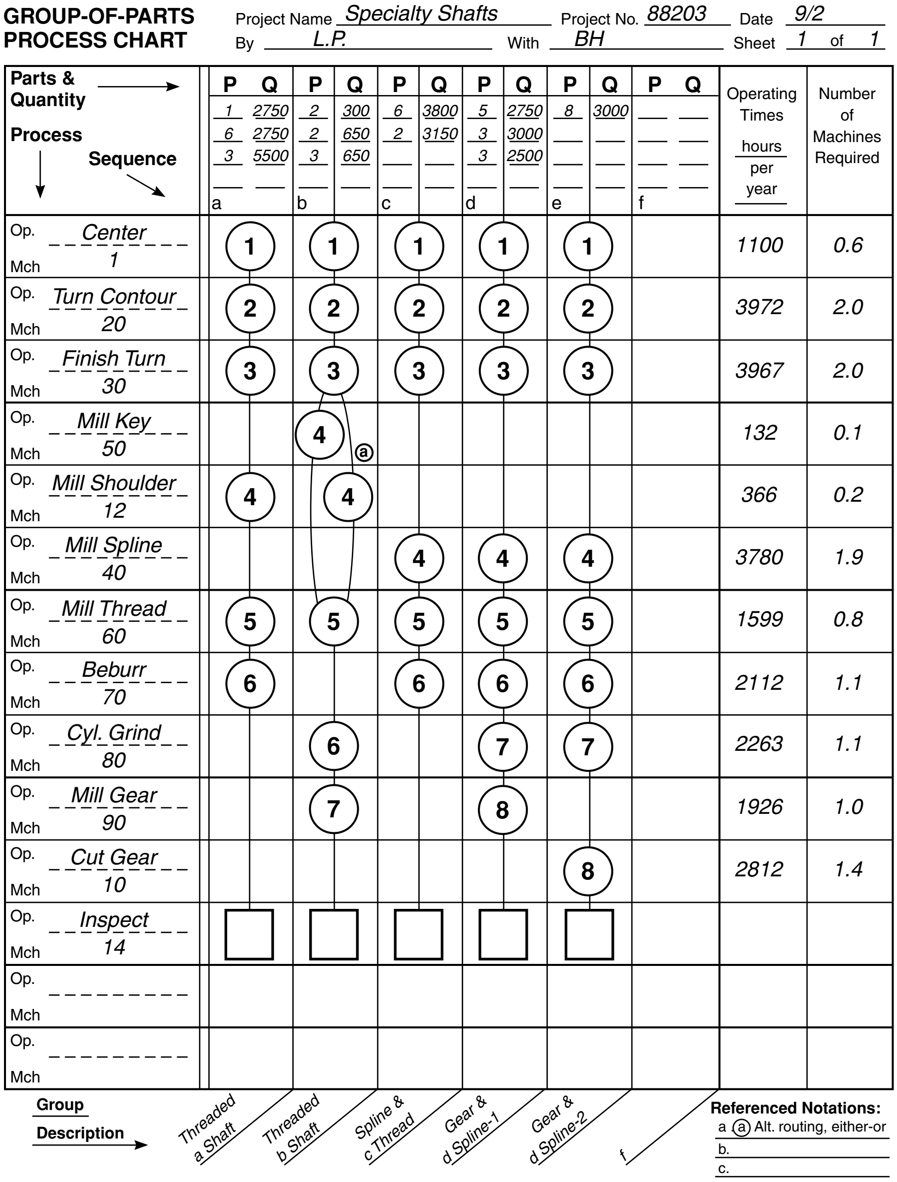

b. Small Parts
a. Oven Halves
Operator 1
d
d. Oven Assemblies
SPOT WELDER THOMSON 190W 14 50 KVA 4008
F
Spot Welder
a
Seam Welder
SEAM WELDER SCIAKY ERS-18 75 KVA 4089
F
a
SPOT WELDER THOMSON 190W 14 50 KVA 4007
F
Operator 2
Spot Welder
c
d. Oven Assemblies
Operator 3
d
c. Backs
b. Small Parts
BENCH
48 x 30
OX
AC
Gas Welder & Small Bench
d
DRILL 1SP P-W NO 4 4016
F
Drill Press
d
Operator 4
BENCH
72 x 30
Large Bench

FIGURE 8.4.5 Equipment and flow diagram. *(© Richard Muther & Associates.)*

When planning a machining or fabrication cell, the group-of-parts process chart is used to illustrate the sequence of operations for each class of parts (see Fig. 8.4.6). The group-of-parts process chart must be accompanied by a capacity analysis showing the types and quantities of machines required by the cell. A simple form of this capacity analysis is shown in Fig. 8.4.7.

When calculating the number of machines, planners must be sure to add allowances for downtime, schedule interference, and changeovers between individual parts and groups of



GROUP-OF-PARTS PROCESS CHART

Project Name *Specialty Shafts* Project No. *88203* Date *9/2*
By *L.P.* With *BH* Sheet *1* of *1*

Parts & Quantity → / Process Sequence	a P	a Q	b P	b Q	c P	c Q	d P	d Q	e P	e Q	f P	f Q	Operating Times hours per year	Number of Machines Required
	1	2750	2	300	6	3800	5	2750	8	3000				
	6	2750	2	650	2	3150	3	3000						
	3	5500	3	650			3	2500						

Op. / Mch	a	b	c	d	e	f	Operating Times hours per year	Number of Machines Required
Op. *Center* Mch *1*	①	①	①	①	①		*1100*	*0.6*
Op. *Turn Contour* Mch *20*	②	②	②	②	②		*3972*	*2.0*
Op. *Finish Turn* Mch *30*	③	③	③	③	③		*3967*	*2.0*
Op. *Mill Key* Mch *50*		④ ⓐ					*132*	*0.1*
Op. *Mill Shoulder* Mch *12*	④	④					*366*	*0.2*
Op. *Mill Spline* Mch *40*			④	④	④		*3780*	*1.9*
Op. *Mill Thread* Mch *60*	⑤	⑤	⑤	⑤	⑤		*1599*	*0.8*
Op. *Beburr* Mch *70*	⑥		⑥	⑥	⑥		*2112*	*1.1*
Op. *Cyl. Grind* Mch *80*		⑥		⑦	⑦		*2263*	*1.1*
Op. *Mill Gear* Mch *90*		⑦		⑧			*1926*	*1.0*
Op. *Cut Gear* Mch *10*					⑧		*2812*	*1.4*
Op. *Inspect* Mch *14*	□	□	□	□	□			
Op. Mch								
Op. Mch								

Group Description →	a	b	c	d	e	f
	Threaded Shaft	*Threaded Shaft*	*Spline & Thread*	*Gear & Spline-1*	*Gear & Spline-2*	

Referenced Notations:
a ⓐ Alt. routing, either-or
b.
c.

FIGURE 8.4.6 Group-of-parts process chart. *(© 1995 Richard Muther.)*

PRODUCT CLASS/DESCRIPTION				MACHINE TYPE										
			Work Center Number>>	1	20	30	50	12	40	60	70	80	90	10
	Part No.	Model	Pieces per Year	Center'g Lathe	Contour Lathe	Engine Lathe	Key Mill	Univ. Mill	Spline Mill	Thread Mill	Drill Press	Cylinder Grinder	Gear Mill	Gear Cutter
Carried forward from Page 2 (hours/year)				750	2159	2775	0	0	3521	718	838	1585	1585	1750
(b) Shaft with gears and threads														
Rear axle gear shaft	147245 153049	LS 20 B 30	300	8	55	28	—	15	—	15	—	123	15	—
Power take-off shaft	136456 170459	L 10 L 20	650	13	108	32	—	18	—	43	—	132	39	—
Auxiliary gear shaft	156097 178905 176890	LS 20 B 20 B 30	650	13	135	74	120	—	—	67	—	149	32	—
(a) Shaft with threads														
Injection pump drive shaft	146785	M 85	2750	42	335	255	—	22	—	1205	275	—	—	—
Steering knuckle arm	146056 145159 145907 145650 145432 145329	L 10 BH 10 L 20 BH 20 BV 20 B33	2750	46	160	225	—	168	—	182	463	—	—	—
King pin	146554 156354 110101	L-B 10 L-B 20 B 30	5500	92	350	275	—	92	—	228	245	—	—	—
Direct Labor (hours/year)				964	3335	3664	120	315	3521	1458	1821	1989	1649	1750
Operators Required				0.5	1.7	1.8	0.1	0.2	1.8	0.7	0.9	1.0	0.8	0.9
Setup, Maint., Downtime, etc. (hours/year)				136	637	303	12	51	259	141	291	274	277	1062
Total Time Per Year				**1100**	**3972**	**3967**	**132**	**366**	**3780**	**1599**	**2112**	**2263**	**1926**	**2812**
No. of Machines Required				0.6	2.0	2.0	0.1	0.2	1.9	0.8	1.1	1.1	1.0	1.4
No. of Machines Available				1	2	2	1	1	2	1	2	2	1	1
Utilization				**55%**	**99%**	**99%**	**7%**	**18%**	**95%**	**80%**	**53%**	**57%**	**96%**	**141%**

FIGURE 8.4.7 Capacity utilization worksheet. *(© Richard Muther & Associates.)*

parts. A good cell capacity plan meets the desired production rate with an appropriate number of machines and level of utilization. Usually the analysis will reveal over- and underutilization of some equipment planned for the cell. If the analysis reveals overutilization, the planner may choose to

- Remove parts from the cell to reduce utilization of the equipment.
- Purchase more equipment.
- Reduce process, changeover, or maintenance times.

If the analysis reveals underutilization, the planner may choose to

- Add parts to the cell to increase utilization of the equipment.
- Remove parts from the cell to eliminate the need for the equipment.
- Change the manufacturing process to eliminate the need for the equipment.
- Leave the equipment external to the cell and route parts to it.

In machining or fabrication cells where the throughput is paced more by the operators than the machines, the cell planner may need to conduct a line balancing exercise, in addition to rough capacity and utilization analyses. In some cases, computer simulation may also be useful to examine the implications of changes to product mix and peaks in production volume.

Once the number of machines has been determined, an equipment and flow diagram is prepared, similar to that shown earlier in Fig. 8.4.5.

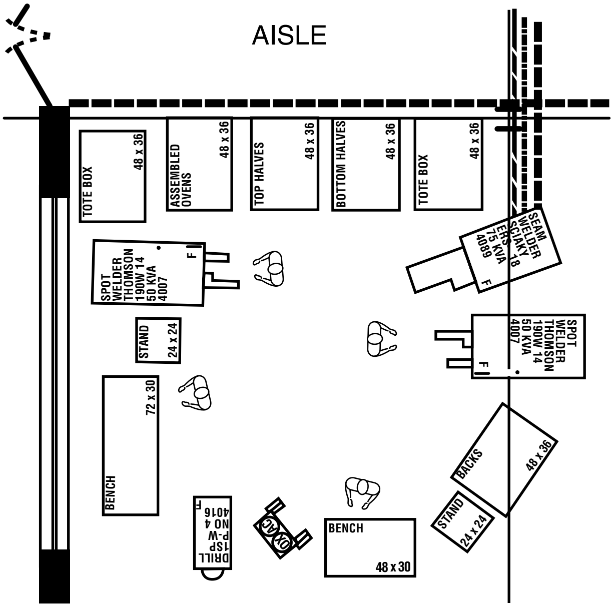
Step 4. Couple into Cell Plans

A cell plan is a coupling of parts and process into an effective arrangement and operating plan. It should include

- The layout of operating equipment (physical)
- The method(s) of moving or handling parts and materials (physical)
- The procedures or methods of scheduling, operating, and supporting the cell (procedural)
- The policies, organizational structure, and training required to make the cell work (personal)

The best way to begin this step is by sketching a layout from the equipment and flow diagram developed in step 3. Once the machinery and workplace layout is visualized, the material handling and any storage methods are determined. Material-handling equipment, containers and storage, or parts-feeding equipment are added to the layout. The planner also adds any support equipment not already visualized in the workplaces, such as tool and die storage, fixture storage, gage tables and tool setup, inspection areas, supply storage, trash bins, desks, computer terminals and printers, display boards, and meeting areas.

Once the layout and handling methods—the physical aspects of cell planning—have been determined, the planning team turns its attention to the procedural and personal aspects. In our experience, the procedural and personal aspects are often more important than the layout and handling in assuring a successful manufacturing cell. These aspects include the procedures and policies for staffing, scheduling, maintenance, quality, training, production reporting, performance measurement, and compensation. In practice, some of these will have already been determined during the layout and handling discussion; the remainder should be clearly defined by the team and approved by management. The documentation of a viable cell plan will also require the resolution of any remaining planning issues listed earlier in step 1. The final output of step 4 is one or more documented cell plans. These will take the form of a layout with associated policies and operating procedures like that shown in Fig. 8.4.8.


AISLE
TOTE BOX
48 x 36
ASSEMBLED OVENS
48 x 36
TOP HALVES
48 x 36
BOTTOM HALVES
48 x 36
TOTE BOX
48 x 36
SEAM WELDER SCIAKY 18 ERS 75 KVA 4089
F
SPOT WELDER THOMSON 190W 14 50 KVA 4007
F
STAND
24 x 24
SPOT WELDER THOMSON 190W 14 50 KVA 4007
F
BENCH
72 x 30
BACKS
48 x 36
STAND
24 x 24
DRILL 1SP P-W NO 4 4016
F
OX
AC
BENCH
48 x 30

Operating Features:

1. Water-cooled seam welder located near column E6 for utility access.
2. Single job classification; all operators cross-trained for all operations.
3. Planned weekly rotation between operator stations.
4. Operators responsible for routine maintenance.
5. Demand spikes to be handeld through overtime.
6. Will gradually reduce lot size after cell is operational.
7. All consumables and tooling to be located in cell with weekly reordering by lead operator.
8. Operators responsible for assembly quality.

FIGURE 8.4.8 Cell layout. *(© Richard Muther & Associates.)*

Step 5. Select the Best Plan

In step 5, the planning team and other decision makers will evaluate the alternatives prepared in step 4 and select the best plan. Typically, this selection will be based on comparisons of costs and intangible factors. Typical considerations include

Investment Costs (and savings or avoidance)

- New production machinery
- Material-handling equipment
- Pallets, containers, and storage equipment
- Auxiliary or support equipment

- Building or area preparation
- One-time move costs, including overtime
- Training and run-in
- Engineering services
- Permits, taxes, freight or other miscellaneous costs
- Inventory increases or reductions (one-time basis)

Operating Costs

- Direct labor
- Fringe benefits and other personnel-related costs
- Indirect labor
- Maintenance
- Rental of equipment or space
- Utilities
- Inventory increases or decreases (annual carrying cost)
- Scrap and rework

Intangible Factors

- Flexibility
- Response time to changing production demand
- Ease of supervision
- Ease of material handling
- Utilization of floor space
- Ease of installation (avoidance of disruption)
- Acceptance by key employees
- Effect on quality

Costs are rarely sufficient for selecting the best cell plan. There are typically too many intangible considerations involved, and in many cases, the costs of the alternative plans fall within a relatively narrow range. In practice, the final selection often rests on intangibles.

The weighted-factor method is the most effective way to make selections based on intangible factors. After making a list of the relevant factors, weights should be assigned to indicate their relative importance. An effective scale is 1 to 10: with 10 being most important. Next, the cell operating team should rate the performance or effectiveness of each alternative on each weighted factor. It is important that ratings be made by cell operators and the appropriate plant support personnel—those closest to the action and responsible for making the selected plan work.

Since ratings are subjective they are best made with a simple vowel-code scale, and converted later into numerical values and scores. The following scale and values are effective:

A almost perfect results (excellent)	4 points
E especially good results (very good)	3 points
I important results (good)	2 points
O ordinary results (fair)	1 point
U unimportant results (poor)	0 points
X not acceptable results	fix or remove from consideration

Rating values are multiplied by factor weights and down totaled to arrive at a score for each alternative plan. If one plan scores 15 to 20 percent higher than the rest, it is probably the better plan. If the costs are acceptable, this plan should be selected. If no plan scores significantly better than any other, then pick the least expensive or most popular, or consider additional factors. The final output of step 5 is a selected cell plan.

Step 6. Detail and Implement the Plan

Once selected, details must still be worked out and preparations made to implement the cell plan. Detailing should begin with an updated, dimensioned drawing of the selected cell layout—typically at a fairly large scale, say 1:50. The detailing step should produce a scaled plan view of each workplace showing

- Normal operator work position
- Location of tooling, gauges, controls
- Parts containers, fixtures, and workplace handling devices
- Utility drops and connection points
- Door swings and access points on control panels and machinery
- Position of overhead lighting

In some cases, an elevation sketch may be useful, showing vertical placement of work surfaces, fixtures, containers, and so on. Where highly fixed machinery is tied together with fixed conveyors, or where robots are used, it may also be necessary to develop a 3D computer model of the cell to simulate or test for interference and proper placement. In light manufacturing cells—machining or assembly—where equipment is easily adjusted during installation, this sophistication is typically unnecessary. Conventional plan views are usually sufficient.

If space is available and time permits, great insight can often be gained by creating a life-size mock-up of the cell, using cardboard, wood, light metal, or plastic tubing. By involving the cell operators in this mock-up, a great deal of useful detailing can be accomplished in a very short time. In our experience, mock-ups provide two significant benefits: (1) They uncover overlooked details that may be expensive to change later in implementation, and (2) they obtain a much greater level of operator involvement and interaction than is possible with an on-screen computer model, or with a 2D plan view of the layout.

Implementing a cell is an opportunity on a relatively small scale to make progress on plantwide improvement initiatives. The cell implementation plan may include tasks, time, and money for the following common improvements:

- Housekeeping and safety—disposition of unnecessary items, fixing of leaks, cleaning and painting of machines, floors, ceilings, machine guards, aisleway guard rails and posts, etc.
- Visual control—marking and striping, signs for machines and workplaces, labeling for tool and fixture storage and containers, signal lights, and performance displays
- Quality management—certification of machine and process capabilities, tool and gauge lists and calibration plans, mistake-proofing and failure analyses, control plans, training, etc.
- Maintenance—repair and rebuilding of machines, replacement of worn-out equipment, preventive maintenance schedules, operator maintenance procedures, etc.
- Setup reduction—videotaping, time study, and methods analysis; redesign of fixtures, tools, and machines; duplication of key equipment, gauges, and fixtures; redefinition of responsibilities; training, etc.

Once the necessary tasks have been defined, they should be assigned to the appropriate individuals, estimated in terms of time and resources, and placed into a schedule, recognizing any dependencies between the tasks. The final output of step 6 is the selected cell plan detailed and ready for implementation.

MORE COMPLEX CELLS

Several considerations can complicate cell-planning projects. Chief among these is the question of how many cells are needed. Given a set of candidate parts and their desired production rates or quantities, the planner must occasionally decide whether a single cell is appropriate, or whether the work should be spread across multiple cells.

When one or more cells feed others, the project becomes one not unlike planning a mini-factory (see Fig. 8.4.9). Additional analysis is required to agree on the material-handling methods and scheduling procedures for moving parts *between* the cells. It may also be necessary to share personnel or equipment capacity *across* the cells being planned. The project may also have to decide on common policies (across all of the cells) for organization, supervision, and performance measurement.

Even when planning a single cell, complications can be introduced if there is a wide range of possible locations for the cell, the appropriate level of automation is unclear, or there is the potential for radical organizational change, such as a move from traditional supervision to self-directed teams.

Four Phased Approach

Complex cell planning projects are best planned in four overlapping phases.

I. Orientation
II. Overall Cell Plan
III. Detailed Cell Plans
IV. Implementation

The scope of these phases is illustrated in Fig. 8.4.10.

Phase I: Orientation. Complex projects or those with very large scope may need an entire phase to determine the best location(s) for the prospective cell(s), the handling to and from, the issues involved, and the plan for planning the cell. Reaching sound decisions may require creating or updating a master plan for the total facility. It may also require some conceptual planning of the prospective cells themselves—hence the overlap with phase II, Overall Cell Plan.

Phase II: Overall Cell Plan. In large or complex planning projects, phase II is used to define the general plan for cellular operations. This includes the number of cells and their respective parts and processes, and the relationships between them. Block layouts are developed along with material handling plans for movement to and from and in between the cells. General operating practices or policies are decided. These planning activities and decisions are not addressed in the simplified six-step approach described in the previous section, How to Plan a Manufacturing Cell. Reaching decisions in phase II may also require some detailed planning and design and therefore overlaps phase III—Detailed Cell Plans.

Phase III: Detailed Cell Plans. Phase III details the individual cell(s) within the selected overall plan. The six-step simplified procedure described previously is highly effective for this purpose. At the conclusion of phase III, the planning team has identified the best detailed plan for each manufacturing cell.

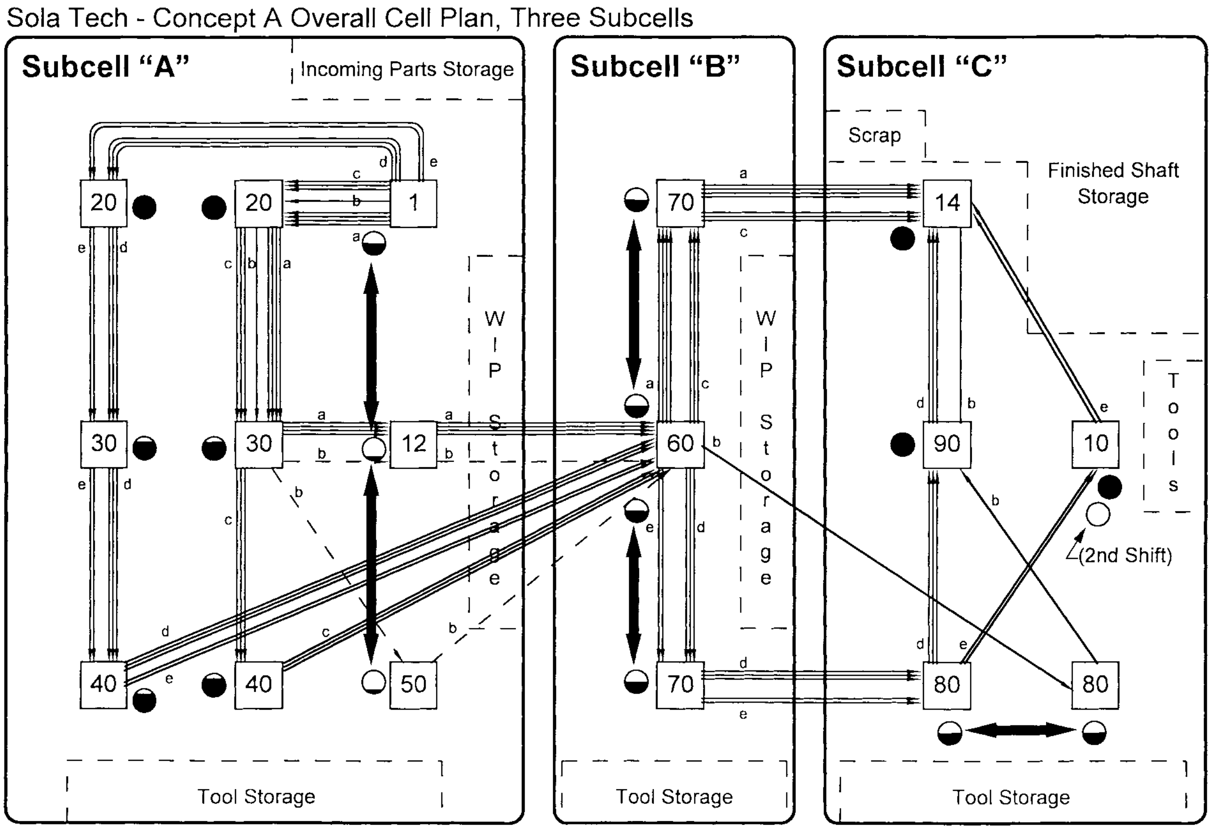

Sola Tech - Concept A Overall Cell Plan, Three Subcells
Subcell "A"
Incoming Parts Storage
Subcell "B"
Subcell "C"
Scrap
Finished Shaft Storage
Tools
WIP Storage
WIP Storage
(2nd Shift)
Tool Storage
Tool Storage
Tool Storage
20
20
1
30
30
12
40
40
50
70
60
70
14
90
10
80
80
a
b
c
d
e

FIGURE 8.4.9 Complex, multicell planning. *(© Richard Muther & Associates.)*

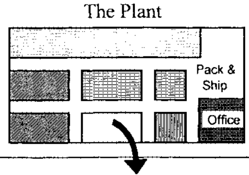
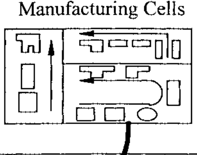
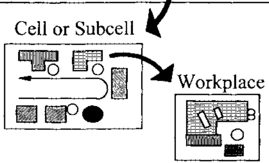
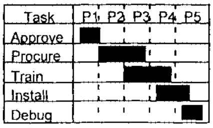
Planning Phases	Scope & Visualization	Outputs
I. ORIENTATION Location, external conditions and planning the planning. The surrounding physical and nonphysical conditions/considerations; plus the objective, situation and plan for planning the cell.		• Objectives • Project plan & schedule • Targeted parts or operational area • Planned location • External conditions • Scope, "givens," or limits of team's authority
II. OVERALL CELL PLAN The general plan for cellular operations. Definition of the cell or cells: how many, what parts, what processes and equipment. Alternative block layouts of space and equipment. Operating relationships and integration between cells and the rest of the plant.		• Definition of cells: what parts, what operations, what equipment • Block layout of cells and supporting areas • Material handling and coupling between cells • Preliminary cell layouts • General operating policies and practices
III. DETAILED CELL PLANS Detail plans and designs for each cell. The detailed arrangements of equipment and workplace design. Specification of detailed operating procedures and methods within each cell.		• Confirmed definition of cell: parts, operations, equipment • Detailed layout for each cell • Material handling within the cells (between work stations) • Detailed operating policies and procedures
IV. IMPLEMENTATION Do; take action on the plans. Schedule, provide, procure, train, install, cleanup, debug...		• Project approval and funding • Detailed implementation plan • Procured equipment • Working cell

FIGURE 8.4.10 Four phases for planning complex cells. *(© Richard Muther & Associates.)*

Phase IV: Implementation. In phase IV, an implementation schedule is defined for each cell. On larger and complex projects involving multiple cells, this schedule may span several months. It will typically include many interdependencies between the individual cell installations, and changes to the surrounding facilities, organization, and management systems. The team then obtains approval and funding, procures necessary equipment and services, directs the physical and procedural implementation, and debugs and releases the cell for production.

Impact of Automation and Technology

Most manufacturing cells consist of conventional, operator-controlled machinery and equipment. However, in some industries and processing situations, highly automated machinery may be used. For example, cells for high volume, repetitive welding may use robots instead of human operators. The same is true with other hazardous operations such as forging. In high-volume assembly of many small or precision components, cells may consist of automated assembly machines, and pick-and-place robots, often connected by conveyors. The entire cell may be computer controlled, with operators providing service and material handling to and from the cell. In some cases, the material handling may be automated using automated guided vehicles.

In between the extremes of all manual or fully automatic operations, cells may include some limited automation for parts feeding and loading, or material handling between operations. A common example is the use of automatic ejection or unloading devices on machine tools. These are typically used to present a completed part to the operator during the same cycle used to manually load the machine. Other examples of selective automation include conveyorized parts washers, curing tunnels, or similar process equipment. Typically the conveyor automates movement between sequential operations without operator intervention or effort, and may drop finished parts into a container.

If an automated cell with computerized controls is planned, extra attention should be given to estimating the costs of equipment, software, systems integration, and to the ongoing maintenance of the system. Adherence to sound technical standards and thorough documentation of all computerized systems will help to keep these costs down. As noted earlier, advanced visualization with 3D computer models is often valuable. Computer simulation may also be used.

Use of automation and advanced technology in a manufacturing cell is most appropriate when the following conditions apply:

- Production volumes are very high, typically above 500,000 units per year, and predictable or steady.
- Product lives are relatively long (before extensive changes or reconfigurations are required).
- Product designs are relatively stable.
- Labor is expensive.
- The company or plant has prior successful experience with automated systems.
- The processes are hazardous or unsafe for human operators.
- Very high repeatability and precision are required.
- The processing technology is stable.

When several of these conditions are met, then at least one alternative cell plan should make use of automation, to be sure that good opportunities are not overlooked.

CHECKLIST FOR CELL PLANNING AND DESIGN

The following paragraphs contain a checklist and brief discussion of the most common choices or decisions to be made when planning or designing a cell. The topics are organized around the three aspects of cell planning discussed earlier: physical, procedural, and personal. The order of presentation follows roughly the order in which the choices and decisions should be made during a planning project—starting with the physical, followed by the procedural, and finally the personal or personnel-related.

Physical Questions

Layout and Flow Patterns.

1. *Which material flow pattern should be used within the cell?*
   - **a.** Straight-through
   - **b.** U-shaped
   - **c.** L-shaped
   - **d.** Comb or spine

   Cells may be physically arranged into one of four basic flow patterns (see Fig. 8.4.11). While the U-shape is frequently advocated and very common, the other patterns do have occasional advantages and appropriate uses. We believe that the best cell layouts are achieved when the planning team forces itself to consider at least two alternative flow patterns, if only to stimulate discussion.

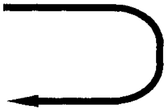
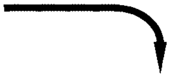
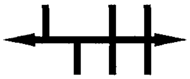
Straight Thru 	1. Easy to understand, follow, schedule, and control. 2. Allows straight, inexpensive handling methods. 3. Easy access on two sides. 4. Easy to expand with a minimum of rearrangement. 5. Avoids congestion at point of delivery and take-away. 6. May minimize space requirements when producing large or bulky products. 7. Can enable a U-shaped plant layout.
U-Shape or Circular 	1. Automatically returns product, holding fixtures, and mobile handling equipment to cell entrance. 2. Delivery and take-away point are the same; allows convenient handling to and from the cell. 3. Workers in center can assist one another. 4. Easier to assign multiple operations to an operator. Allows easier line balancing.
L-Shape 	1. Allows fitting lengthy series of operations into limited space. 2. Lets feeding cells start on an aisle and end at point of use. 3. May allow isolation of dangerous or costly-to-move equipment in the elbow, with savings in implementation cost and/or two directions for expansion.
Comb or Spine 	1. Lends itself to two-way flow. 2. Well suited to cells with highly variable routings. 3. Allows "fingers/teeth" to be segregated for special requirements.

FIGURE 8.4.11 Basic cell flow patterns. *(© Richard Muther & Associates.)*

2. *How does the choice of flow pattern fit with the overall plant layout and material flow?* When deciding on the internal flow pattern for each cell, do not overlook its relationship to and impact on the overall plant layout. The layout of aisles and general flow pattern in the factory may favor or even force a particular flow pattern within the cell.

Handling and Storage.

1. *What are the groups or classes of material to be moved?* General categories to be examined include

- **a.** Incoming parts and materials to the cell
- **b.** Work in process between workstations within the cell
- **c.** Outgoing parts and materials leaving the cell

Classes should be defined with an eye toward common handling and storage methods. The classes for work in process should have already been defined through parts classification and analysis of the process. But a review of incoming and outgoing parts and materials may introduce additional classes not yet identified or considered.

2. *What handling equipment should be used for each class of material?* Typical choices include forklifts, tugs and carts, pushcarts, walkie pallet jacks, conveyors, slides, chutes, overhead handling devices, or simply the operators themselves—hand carrying parts or materials.
3. *What containers or transport units will be used?* Typical choices include pallets, skids, bulk or large containers, small containers and totes, cartons, or in some cases, the items themselves.
4. *Where and how will materials be stored or staged?* What equipment will be used? Typical choices include the floor, flow racks, shelves, pallet racks, cabinets, cartridges or magazines integrated directly into machines, or directly on workbenches themselves.
5. *How much material will be staged or stored?* Typically expressed in minutes, hours, or days of coverage at an expected production rate.
6. *How much staging or storage space will be required?* And where should it be placed in the layout?

Supporting Services and Utilities.

1. *What process-related supporting services are required?* Space and equipment are often required for tool and die storage, fixture storage, gage tables and benches, tool setup, inspection areas, supplies, trash, and empty containers.
2. *What personnel-related supporting services are required?* Typical services include shop desks and work areas, team meeting area, computer terminals and printers, telephones and public address speakers, document storage, and bulletin boards.
3. *What special utilities are required?* Water and drains? Special electrification? Special ventilation or exhausts? Lighting?

Procedural Questions

Quality Assurance/Control.

1. *Who will be responsible for quality?* Will operators inspect their own work? Each other's work? Or, will dedicated inspectors be used? From within the cell or from outside?
2. *What techniques will be used?* Techniques may include visual monitoring, statistical process control, or mistake-proofing.
3. *Will special equipment be required?*
4. *What specifications or procedures are relevant or should be incorporated into the plan?*

Engineering.

1. *Who is responsible for engineering the parts and processes involved?* Product engineering? Manufacturing/process/industrial engineering?
2. *How will tooling be managed?* Externally by a central organization, or internally within the cell? Will tools be shared or dedicated to each machine?
3. *Where will tools be stored?* External to the cell? Internal? Centrally or at each workplace or machine?
4. *Who will be responsible for setup?* External or internal specialists? Operators themselves? Teams?

Materials Management.

1. *How will production be reported?* Aggregate or total units only? Each unit as completed? First and/or last operation as performed? At the completion of each operation?
2. *How will reporting be accomplished?* Using paper forms? Key entry? Bar code scanning or other electronic method?

3. *How will the cell be scheduled and by whom?*
4. *How will specific parts and jobs be sequenced?* Who will be responsible?
5. *Is line balancing needed?*
6. *What is the strategy for workload and capacity management?* How will the cell respond to changes in product mix, bottlenecks, and peaks?
   - **a.** With extra, idle machine capacity?
   - **b.** With extra labor or floating personnel?
   - **c.** With overtime?
   - **d.** With help from adjacent cells?
   - **e.** By off-loading work?
   - **f.** By building ahead to inventory?
   - **g.** By rebalancing or reassigning operators?

Maintenance.

1. *Who will be responsible for maintaining machinery and equipment?* External by a central organization, or internally by cell operators?
2. *Have specific maintenance duties and frequencies been defined?*
3. *Who will be responsible for housekeeping?* Cell operators or external personnel?
4. *Are preventive maintenance procedures required?*
5. *Are statistical or predictive maintenance procedures appropriate or necessary?*
6. *Will the cell require special equipment or services to hold or recycle waste, chips, oils, coolant, scrap, and so on?*

Accounting.

1. *Will new accounting or reporting procedures be required?* For costs? For labor? For material usage?
2. *Will the cell be treated as a single work or cost center for reporting purposes?* Or, will costs be charged to specific operations within the cell?
3. *Will labor reporting distinguish between direct and indirect activities?*
4. *Will labor be reported against specific jobs or orders?*
5. *Will inventory be charged or assigned to the cell?* Will the cell be a controlled inventory location?
6. *How will scrap and rework be tracked and reported?*

Personnel-related Questions

Supervision and Performance Measurement.

1. *Will the cell have a designated supervisor or team leader?* Or will the cell operate as a self-directed team?
2. *How will cell performance be measured and reported, and to whom?*

Job Definitions and Assignments.

1. *Will new positions be required?* Have they been defined?
2. *Will cell operators be specialists or cross-trained to work anywhere in the cell?*
3. *Will operators rotate assignments on a regular basis?*

PLANNING A MANUFACTURING CELL

4. *How will the initial cell operators be recruited or assigned?* Will the opportunity be posted plantwide?
5. *How will future operators be assigned?*

Compensation and Incentives.

1. *Will operators be compensated on a different basis from other parts of the plant?*
2. *Will operators be paid for skills or cross-training?*
3. *Will a group incentive be used?* How will it be calculated?

Systematic Planning and Involvement

The cell planner can generally achieve a good result by planning each individual cell with the six-step procedure outlined previously. If the project is large or complex, and involves multiple cells, the additional structure of four overlapping phases will be helpful. As each cell is planned, look first at the physical, then the procedural, and finally at the personal aspects of the project. At every step, the planner should involve prospective operating personnel and others from the relevant supporting groups. Working as a group to answer the outlined questions will ensure that the final, selected plan will have a smooth implementation and deliver the benefits desired.

Role of the Industrial Engineer

In many cases, the industrial engineer may serve as the primary cell planner. But for best results, production personnel should play leading roles in planning their own cells. When operators and first-line supervisors lead the project, the industrial engineer plays an important supporting role, typically focused on the analytical steps and physical aspects of the cell plan. The IE will often lead or perform much of the work on

- Classification of parts
- Definition of processes and routings
- Capacity analysis
- Layout planning

The industrial engineer may also assist in developing operating procedures, and will often provide cost estimates and comparisons of costs and savings among alternative plans.

CONCLUSIONS AND FUTURE TRENDS

By moving operations closer together, manufacturing cells reduce material handling, cycle times, inventory, quality problems, and space requirements. In addition to these primarily quantifiable benefits, the focused nature and typically small size of cells also leads to

- Easier production control
- Greater operator productivity
- Quicker action on quality problems
- More effective training
- Better utilization of personnel
- Better handling of engineering changes

Because of these benefits, cells provide a focused and practical way to implement the principles of the Toyota production system, lean manufacturing, world-class manufacturing, just-in-time, and other forms of plantwide productivity improvement. Visual management and control, elimination of waste, setup reductions, pull signals, and continuous flow are all easier to achieve when implemented through individual manufacturing cells. The popularity of plant- and companywide improvement programs will continue to expand the use of manufacturing cells.

Because they are relatively quick and easy to reconfigure, cells have become the preferred manufacturing model for high-variety, medium-to-low volume, short-life-cycle products. Increasing marketing emphasis on highly tailored, relatively low-volume products will also expand the use of manufacturing cells.

REFERENCE

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FURTHER READING

Hales, H. Lee, William E. Fillmore, and Bruce J. Andersen, *Planning Manufacturing Cells,* Society of Manufacturing Engineers, Dearborn, MI, in press, text and videotape set.

BIOGRAPHIES

H. Lee Hales is president of Richard Muther & Associates and coauthor with Richard Muther of the book *Systematic Planning of Industrial Facilities (SPIF)* and the videotape set *Fundamentals of Plant Layout* produced by the Society of Manufacturing Engineers. Formerly materials and operations manager for a large equipment supplier, Hales has assisted a wide variety of manufacturers in planning and implementing improved operations and facilities. He is a senior member of the Institute of Industrial Engineers and is a past division director for Facilities Planning and Design. Hales holds B.A. and M.A. degrees from the University of Kansas, and an M.S. from the Sloan School, Massachusetts Institute of Technology.

Bruce J. Andersen, CPIM, is an experienced manufacturing and facilities consultant with Richard Muther & Associates. Formerly a production engineer, Andersen has helped leading companies in a variety of industries to make improvements in inventory and production management, facility layout, and the implementation of manufacturing management systems. He is a member of the American Production and Inventory Control Society (APICS) and the Institute of Industrial Engineers. He holds a B.S. in mechanical engineering from Duke University and an M.S. in computer-integrated manufacturing from Georgia Tech.

William E. Fillmore, PE, is a leading authority on the planning of manufacturing cells and a consultant in this field with Richard Muther & Associates. He has provided assistance on more than 100 cell plans and implementations. Fillmore is author of the booklet *Results-Based Improvement,* and coauthor of the booklet *Simplified Systematic Planning of Manufacturing Cells.* He is a charter member of the Institute for High Performance Planners, and has served on the College-Industry Council on Material Handling Education. Fillmore holds a B.S. in industrial engineering from Kettering University, and has done graduate work in the field at the University of Missouri.

Source: MAYNARD'S INDUSTRIAL ENGINEERING HANDBOOK

CHAPTER 8.5

CASE STUDY: RELOCATING AND CONSOLIDATING PLANT OPERATIONS

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The company highlighted by this case study manufactures antivibration systems. Every product is a combination of metal, plastic, and rubber components. The products and processes are very similar in three of the plants. However, the plants do not fully utilize their available capacity. Considering the current market conditions, it is obvious that utilization would not increase. Therefore, the decision was made to consolidate the three plants into one.

This case study will focus on (1) the process of gathering necessary information using such powerful tools as the statistical process analysis (SPA) and the MOST® work measurement systems to guarantee a successful relocation, (2) the planning of the project, and (3) implementing the consolidation/relocation plan. The most important aspect to introduce is the systematic approach and the paradigm change from the univariate to the multivariate method used to accomplish the analysis, planning, and realization of the consolidation activities.

BACKGROUND AND SITUATION ANALYSIS

Company and Product Information

The company providing this case study manufactures antivibration systems for transportation equipment, machinery, rail vehicles, stationary combustion engines, aeronautical products, and the like. Each product is a combination of metal, plastic, and rubber components, which absorb the vibrations caused by engines in the stationary case and the vibrations caused by engines, roads, or rails in the case of mobile systems. The operating plants A, B, C, D, . . . are units of the company. Each plant is considered a network of manufacturing and service processes, such as production, management, production planning and control, maintenance planning and control, as well as industrial engineering, research and development, financial planning and control, and other processes.

The customer requirements and the numerous different applications of the antivibration products result in a large number of product classes. These classes are defined with respect to the absorption of the oscillation (static and dynamic stiffness), stability of connection (compression set), and specific construction, as well as specific installation and product geometry and the properties of the product components (metal, plastic, adhesive, and rubber). Apart from these classes there are product groups concerning the usage and the required manufacturing processes.

Why Restructure the Production?

The plants A, B, and C primarily manufacture identical or similar products. Therefore, the manufacturing and service processes are also identical or similar. In addition, these plants compete in the same market. Many problems exist.

The company's product list contains about 6000 different products. However, only 2000 different products will be manufactured annually and only about 800 different products are produced consistently every year. These make up about 95 percent of the sales volume and also about 95 percent of the revenue. However, for the manufacturing of these 800 different products, the company needs only about 60 percent of its manufacturing capacity. Therefore, 1200 of the remaining 5200 different products will be ordered randomly throughout the year. Nevertheless, the company needs a production plan. The relationship between the sales, revenue, capacity, and number of different products for plants A, B, and C, which produce identical or similar products, are summarized in Table 8.5.1

TABLE 8.5.1 Sales and Capacity in Plants A, B, and C

	Permanent products		Randomly ordered, planned products, types	Manufactured products	
Plant	Types	Capacity %		Types	Capacity %
A	150	70	200	100	40
B	250	50	500	400	20
C	400	60	500	700	45

This table shows that the utilization of capacity varies randomly as well. At times the plants may have excessive capacity and at other times a lack of capacity. The actual figures for the overall *productivity* in the factories were less than 40 percent, which can be explained by low levels of work measurement and planning of the production orders, low capability indexes, and minimal design of processes. Approximately 80 percent of all orders have

- Insufficient coverage of time standards.
- Insufficient data.
- Incorrectly calculated process capability indexes. (Only one product parameter was used for the calculation—against better judgment. Each product should be described by more than one parameter.) Therefore, the wrong decisions were made for process improvements or control of the processes by control charts on the basis of the process capability indexes.
- Extreme variations in product types.

The return on investment (ROI) is dependent on the magnitude of investments, productivity, innovations, market position, and market growth. A calculation of the ROI resulted in a range of 0.2 percent < ROI < 5 percent. These values are clearly too low, particularly since the market share cannot be increased. The financial analyses, as well as the ROI, show that the expenditures of the company have to be reduced immediately.

Other main problems included the following:

- The productivity in plants A, B, and C ranged between 30 and 60 percent.
- Because of random ordering of different products during the year, an over- or undercapacity utilization will occur in the plants with respect to labor, machines and materials.
- The process capability indexes (see Ref. 1 and the product capability indexes in Ref. 2 and Chap. 14.3) are smaller than 1. That means that the reject rate of products is too high, because many of the products do not meet the (internal and external) customers' requirements expressed by the nominal values and tolerance limits for all product parameters.
- The labor costs are too high.
- The processes are controlled on the basis of experience instead of using the process equations, with the nominal values of all product parameters as the target values resulting in low capability indexes.
- The communications between plants and between processes within the plants are inefficient and based on past practices. Therefore, for instance, the specification of all relevant customer requirements by nominal values and tolerance limits is poor.

The main problems are not independent of each other and occur in all of the company's plants. Solutions to these problems are necessary to secure the existence of the company.

Strategies and Alternatives

The problems could be solved for each individual plant. This would, however, mean that parallel work has to be done with loss of labor, material, and money as a consequence, because the three plants manufacture similar products. Therefore, management decided to relocate the three plants into a new facility. This decision resulted in no wasted time for parallel efforts, a reduction of costs, and an increase in productivity. This can be achieved by an increase of the capability indexes through an improvement of processes and communication between the processes and a grouping of similar products and manufacturing processes using group technology principles and fractals.

As conditions for the relocation, the relocated processes must be maintained, and powerful tools such as portfolio analysis, including Pareto analysis and benchmarking, SPA (statistical process analysis), and MOST should be applied. These are required to realize the paradigm change from a functional production system to a network of processes with effective communication between the processes (see Chap. 14.3) and the transition from a hierarchical to a process-oriented organizational structure.

Why Relocate in Germany?

The three plants—A, B, and C—that produce similar products are located in Germany. The specialists in the development and manufacturing of these complicated products, the highly trained workers, the expertise in the application of SPA, and the relocation process are all available in Germany. The knowledge about the products, processes, and methods needs to be preserved. Although German labor costs are among the highest in the world, management believes that it is possible to operate profitably in Germany, if the modern production technologies and the scientific management methodology described previously is applied.

OBJECTIVES AND SCOPE

Overall Objective Based on the Selected Alternative

The overall objective of the relocation and consolidation of the three plants is to increase productivity, profitability, and competitiveness through the application of modern management methods.

Solutions to the defined problems are necessary to enhance the prospect of the survival of the company. Solutions are often expensive. Therefore, after ranking the problems, the most important problems have to be solved first.

The basis for the overall objective is an analysis of the market and the company with respect to present status and future developments.

The answers have to reflect the requirements of the market progression with respect to the functionality of the antivibration products, their prices and reliability, and the achievement of those requirements by the company. The requirements will include time for the adaptation of product modifications and the attainment of financial indexes, such as profitability.

The answers also have to cover the adaptation of the production resources to market conditions based on a product quantum analysis (PQA), which is a classification of the different products according to their volumes by using the Pareto analysis of sales, costs, and profits.

Specific Project Objectives

For the simplification and improved transparency of the product catalog, the diversity of products have been classified as follows:

Status of production (SP)
Strategic manufacturing units (SMU)

The SP classifies the manufacturing of the product according to the product development cycle—product development, testing, model products, series production, and so on in analogy with

$$\text{SP} = \begin{cases} 1 \text{ development} \\ 2 \text{ installation} \\ 3 \text{ series} \\ 4 \text{ spare parts} \\ 5 \text{ short series} \end{cases}$$

The SMU classifies the same products according to the status of product manufacturing, which means that a product can be produced or not, or can be cancelled from the product catalog, as follows:

$$\text{SMU} = \begin{cases} 0 = \text{inactive} \\ 1 = \text{active} \\ 2 = \text{cancelled} \end{cases}$$

The results of the PQA will influence financial indexes such as productivity. The process and product capability indexes have to be increased. The process capability indexes, as an expression of the inherent potential of a process to produce products that have met predetermined standards, are derived from a comparison between the projected target and the actual level of manufacturing. The definition of the *product capability indexes,* as the simultaneous comparison of all tolerance limits with the width of the multidimensional distribution of all product parameters, is the definition of *quality* as viewed by Jahn [2]: "conformance to *all* requirements." Therefore, an increase of the product capability indexes will lead to an improvement of quality. The increase is possible through the control or specification of all relevant customer requirements by the calculation of the nominal values and tolerance limits for all relevant product parameters. As another alternative, the increase is possible through the improvement of the processes in the network by the application of the SPA methods to reduce the variability of all product parameters. The third alternative is to balance the processes so that the mean and nominal values for all product parameters become approximately the same.

Costs for the products and labor have to be reduced. Before this can be done, the costs have to be calculated. This is possible by applying the SPA and MOST methods. The processes have to be controlled by using the process equations and applying the SPA methods with the nominal values of all product parameters as the target values. The productivity cube in Fig. 8.5.1 shows that an improvement of the methods level through specification of all customer requirements, control of the processes in the network, proof of conformance to all customer requirements, improvement of the portfolio analysis, and so on will lead to increased performance and utilization and consequently to higher productivity.

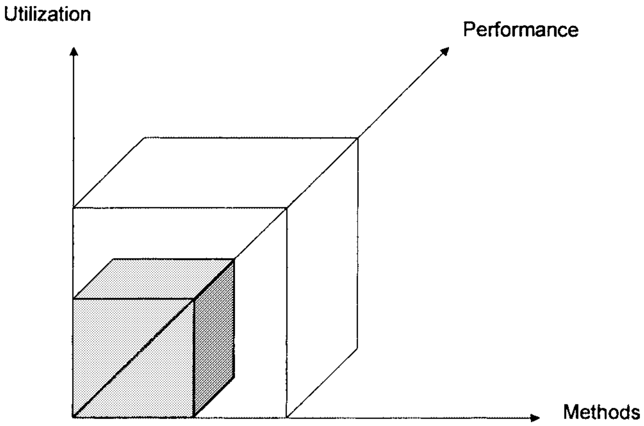

FIGURE 8.5.1 Productivity cube.

Plants, Products and Processes Covered

To achieve productivity improvement, quality improvement, operational effectiveness, employee involvement, and cost reduction, the SPA and MOST methods have to be applied. In addition, analyses of the capacity, maintenance, and suppliers are necessary. Management decided to cooperate with a consulting firm to analyze the actual condition of the plants, structure the new relocated plant as a network of manufacturing and service processes, improve the processes, devise a complete study of the product spectrum, and direct the entire project.

The reality of modern production and service processes has simply transcended the relevance and utility of the respected but ancient management tools. In relation to the relocation, the most important questions are

How many production areas are there?
How many are actually needed?
Which actions have to be performed?

Advantages and disadvantages should be considered when answering these fundamental questions. For instance, some of the advantages are

- Productivity improvement, cost reduction, and savings of investment funds through problem solutions and synergy effects
- Reduction of transports between the plants within the company and raising the level of maintenance
- Adjustment of the portfolio

Examples of disadvantages are

- Resistance to a major change
- Initial work is mostly research and development
- Interrupted manufacturing during the relocation period
- Worker layoffs and relocations

It will be necessary to overcome these disadvantages.

ORGANIZATION OF PROJECT

Organization of several teams and in-depth planning were necessary to successfully complete such a large-scale project as this.

Steering Committee and Project Teams

Four teams directed by a steering committee, consisting of five persons from management, completed the work. The first team was made up of two external specialists and staff people from the company for the application of SPA and MOST as well as plant layout planning and network engineering. The development teams consisted of industrial engineers and representatives from the maintenance, production planning and control, data management, material flow and logistics, budget and financial control, human resources, purchasing, marketing and sales, and information and training functions. The temporary team was composed of external and internal craftspeople. Other resources utilized were the CAD system and vehicles for transportation of the equipment and machines.

Planning and Scheduling

Following the preliminary investigation, the improvement of the processes, and the reorganization of the plant into fractals, the relocation project had to be completed within two years after the decision to proceed was made. The preliminary investigation started at the beginning of 1998. The process improvements and the relocation of the three plants A, B, and C to plant C′ had to be completed by the end of 1999. The detailed activities were planned and scheduled using recognized project management procedures and Gantt diagrams. The relocation of plant A had to be concluded before the end of 1998. In the same year, the technical preparation, such as the infrastructure for the relocation of B to C′ and C to C′, had to be completed as well. The investment budget including the budget for new processes was about $20 million (35 million DM).

Information and Training

The project teams reported the progress of each subproject to the steering committee on a weekly basis. Approximately 120 workers in the manufacturing and service processes had to be trained in the following areas:

- The plant as a network of manufacturing and service processes
- The communication between processes regarding
    - Data collection, data management, and data processing
    - Simple statistical tools, such as cause-effect diagrams, flow diagrams, frequency histograms, and summary statistics
    - Specification of customer requirements
    - Control of the processes
    - Proof of conformance to all customer requirements
- Total quality management systems
- Annual assessments of quality, particularly of their own work

The Role of the Works Council

The works council, in German *Betriebsrat,* is a group of elected employees who represent the interest of the workers—for instance, the observance of the rules of the agreement between employees and top management. The works council has no involvement in management decisions, but management has to inform the works council about the company's financial situation and rationalization projects, and also about the relocation of the plants. Consequently, the works council has been involved in discussions with the steering committee, the team of specialists, the research and development teams, and the consulting team.

PROCEDURES AND APPLICATION OF TOOLS

Overview of the Relocation Approach

The solutions to the problems in the problem hierarchy required different methods based on industrial engineering disciplines, mathematical statistics, economics, management practices, and primarily, multivariate statistics in connection with the relocation project.

Industrial engineering methods that were required were portfolio analysis and management. These included benchmarking and Pareto analyses, capacity analyses, and maintenance audits. Also, similar processes from the entire network of manufacturing processes were combined using group technology principles. Other manufacturing and service processes were put together in a network of fractals, using layout models. These methods include the use of the MOST system and financial analysis.

For the overall capability analysis, the process capability indexes and their multivariate relationship to the product capability indexes were required. Specifications of the customer requirements through the calculation of nominal values and tolerance limits for all relevant product parameters were also needed, as well as correlation and regression analyses and the selection of optimal subsets of input, process, and product parameters. The improvement of the communication between the process owners is a management responsibility. Data collection, a summary of requirements related to the customer requirement profiles, specification and control of the processes, proof of the conformance to all relevant requirements, and the transition from a hierarchical to a process-oriented organizational structure were included, in addition to the analysis of costs, productivity, profitability, and so forth.

Purpose and Use of Selected Specific Tools

Since not all required tools can be described in detail in this case study, the reader is referred to Chap. 14.3 for additional information on SPA and Chap. 17.4 on MOST. The relocation project started with industrial engineering subject matters. From a practical point of view, the portfolio analysis was one of the first tasks.

The most important aspect of the product quantum analysis (PQA) was the forecast for the specific market sector of the company. The growth of the market will generate an increased demand for company products. With regard to the portfolio management, an analysis of all three factories had to be carried out to determine the potential of each plant. Based on the economical potential for growth, this analysis investigated the market share of the company, with focus on a defined status of manufacturing and levels of production.

For the product mix prior to the relocation, only the total volume was considered, without the status of production (SP) and strategic manufacturing units (SMU) classifications. The classification of the 6000 antivibration products in SMU and SP produced the following result:

$$\text{SMU} = \begin{cases} 0 \text{ approximately } 15\% \text{ (inactive)} \\ 1 \text{ approximately } 20\% \text{ (active)} \\ 2 \text{ approximately } 65\% \text{ (cancelled)} \end{cases}$$

The 20 percent active SMU were classified in SP categories as follows:

$$\text{SP} = \begin{cases} 1 \text{ approximately } 10\% \text{ (development)} \\ 2 \text{ approximately } 0\% \text{ (installation)} \\ 3 \text{ approximately } 25\% \text{ (series)} \\ 4 \text{ approximately } 50\% \text{ (spare parts)} \\ 5 \text{ approximately } 15\% \text{ (short series)} \end{cases}$$

Consequently, more than 4800 of the total 6000 classified products play no significant role in the market.

The portfolio analysis was carried out using SP 3, 4, and 5. The total market volume of 500 million units per year, corresponding to a market value of $1.5 billion, is shared by six competitors.

The analysis of the company and its position in relation to its competitors justified improvements, investments, and relocation of the production facilities. Similarly, the relationship between the actual market share and the return on investment (ROI) revealed important information that supported these decisions. This analysis shows that approximately one-third of all the products retains a market share of 80 percent; while the market share for all the other products combined is less than 20 percent. The fact that increasing product volume leads to decreasing product costs must be considered in this context.

Based on these findings, the product catalogs, database, and documentation were revised, and an equipment list for the company was compiled. Both the sales and purchasing departments were requested to notify customers and suppliers about the new situation.

Only the potential for growth in the SP1 classification was included in the analysis of the development projects. A decision that 50 products should be developed in SP1 was made. Likewise, 15 products should be introduced in SP2 during the next two years. In the actual profit plan, the sales volume is equal to 200 million products per year. The capacity planning is based on the core production, which is concentrated in the power press department. Approximately 140 power presses, which should produce the annual volume, were distributed throughout the factories. However, the power presses were not specified according to the process cycles and/or their capacities.

The three plants were characterized by the number of machines used for the core processes, the number of different products produced, the number of workers allocated for production and services, sales volumes, turnover rates, and plant space. This data is collected in Table 8.5.2.

TABLE 8.5.2 Characteristics of Plants A, B, and C and Planned Requirements for Plant C′

Plant	Machines for core processes	Number of different products	Workers in manufacturing	Services employees	Sales, products, ×1000	Turnover, million DM	Plant area, m^2
A	32	350	140	80	35,000	85.50	70,000
B	67	750	320	190	75,000	183.75	110,000
C	79	900	370	200	90,000	220.50	220,000
Total	178	2000	830	470	200,000	490.00	400,000
Planned for C′	140	2065 (1265 planned at random, 800 permanent)	550	150	232,000	522.00	220,000

Subsequently, we determined the new product mix, sales volumes, and other resources needed on an annual basis for plant C′ as shown in Table 8.5.3. Based on the projected product mix, optimal numbers of machines and workers, as well as information (database) and production areas, were established. The projected volumes for sales and purchase planning are summarized in Table 8.5.4.

TABLE 8.5.3 Annual Demand for Products, Sales, Machines, and Workers

	SP 1	SP 2	SP 3	SP 4	SP 5
Product types/year	50	15	300	720	180
Sales, products/year × 1000	25.000	7.000	160.000	10.000	30.000
Power presses	20	5	120	5	15
Workers, production	95	25	600	50	100
Workers, service	20	10	200	20	30

To fully comprehend this case, it is important to understand the main principles for planning the processes. A prime example is the manufacturing of bushings, which includes joining a mixed rubber compound with a fabricated metal component to a final product—a bushing. In addition to this main process, a variety of auxiliary processes need to be performed, for instance, metal preparation with chemical substances and/or posttreatment of the final product. The production category will depend on the product. There are five production categories: SP1 to SP5. As a benchmark, a specific bushing of a determined geometrical dimension, which is in high demand, is used.

There are three core processes—in process I the rubber is mixed, in process II the metal components are fabricated, and in process III the metal, rubber, and plastic components are assembled. The new product mix after improvements was defined for SP3. The products man-

TABLE 8.5.4 Product Mix and Projected Sales Volumes

	SP 1	SP 2	SP 3	SP 4	SP 5
Product types	50	15	300	720	180
Sales, products/year ×1000	25,000	7,000	160,000	10,000	30,000
Sales, million DM/year	75,000	25,000	300,000	50,000	100,000

ufactured in the new plant C′ are classified in product groups as specified in the product catalog. The manufacturing processes producing these groups have to be formed using group technology principles, according to multivariate product and process specifications. That means that in C′ all 140 required machines for the core production and all other machines and equipment have to be reinstalled based on group technology principles. If the most important service processes for the core production are classified according to the same principles, and if identical or similar manufacturing processes are established, we will have a network of identical or similar processes. Such a network complete with work instructions and assigned labor is called a *fractal,* which is a useful and feasible production unit built on the basis of group technology principles [3,4].

Another method of creating fractals could be through a combination of other processes, work instructions, and labor based on group technology principles.

Each fractal is defined as the smallest possible unit that includes all functions that are necessary for the manufacturing of a complete product. Therefore, C′ has become a plant of fractals or a plant consisting of the smallest possible units for all pertinent product groups.

After having established the model of fractals, the number of workers required in the manufacturing and service processes needed to be determined. Table 8.5.3, which is divided into five rows (e.g., annual product types, sales volumes, machine capacity, and number of workers for production and service), contains the data for SP 1 to 5.

The total number of employees working in the former manufacturing plants has been reduced from 830 to 750 working in C′, and the number of service workers (470) has been reduced to 250. The reduction was facilitated by the fact that not all employees relocated from A and B to C′.

The personnel distribution is based on data presented in Spencer's book [5]. For each group of workers, a capability profile had to be worked out so that the capabilities could be determined for each worker in the manufacturing and service processes. The resignation of workers had to be balanced by the employment of new workers. All workers in the new plant had to be trained in group technology principles and manufacturing in fractals, as well as in the application of the simple statistical tools for the inspection of their own work.

Of the total maintenance expenditures, only about 10 percent were used for preventive maintenance. Ninety-five percent of the entire inventory was reserved for more than 80 percent of the spare parts. Moreover, 80 percent of all spare parts were spare parts for machines, which are older than 15 years. This was a confirmation of a low efficiency level. The six following maintenance functions were defined and introduced:

1. Inspection
2. Service
3. Preventive maintenance
4. Repair
5. Replacement
6. New installation

This convinced the team that more than 80 percent of future maintenance work had to be in the preventive field. This suggests that more than 80 percent of the maintenance work will fall into categories 1 to 3.

The maintenance cost analysis suggests that planning and accounting were performed through the repair orders. This convinced the team that consistent process evaluation can improve productivity by approximately 50 percent, meaning that the present performance of approximately 60 percent can be increased to approximately 90 percent. By accomplishing this, the machine capability index C_{mk} will also increase.

The points of time for preventive maintenance cannot be planned through benchmarking. Therefore, no capability analysis for maintenance was performed. This initiated a proposal to the company management team to launch a new project MPC—Maintenance, Planning, and

Control with the objectives to

- Plan preventive maintenance by using deficiency statistics and renewal theory
- Introduce capability analysis
- Implement repair control

The maintenance of machines and processes has to be accomplished in accordance with the prevention plan including

Material and information delivery
Methods and adjustment of process parameters
Manufacturing procedures
Marking the processes, machines, workplaces, and equipment areas in different colors

Next, plant layout models and networking techniques were applied. The starting point for the plant layout design involved group technology principles based on product groups or families. The product components consisting of metal, plastic, and rubber were also classified according to the same principles. The group technology model for components and products is depicted in Fig. 8.5.2. The model shows the summary of inputs and the interlinked manufacturing processes for specific product groups. Using the symbolic representation of workplaces and manufacturing processes, the layout representation based on the group technology concept is illustrated in Fig. 8.5.3.

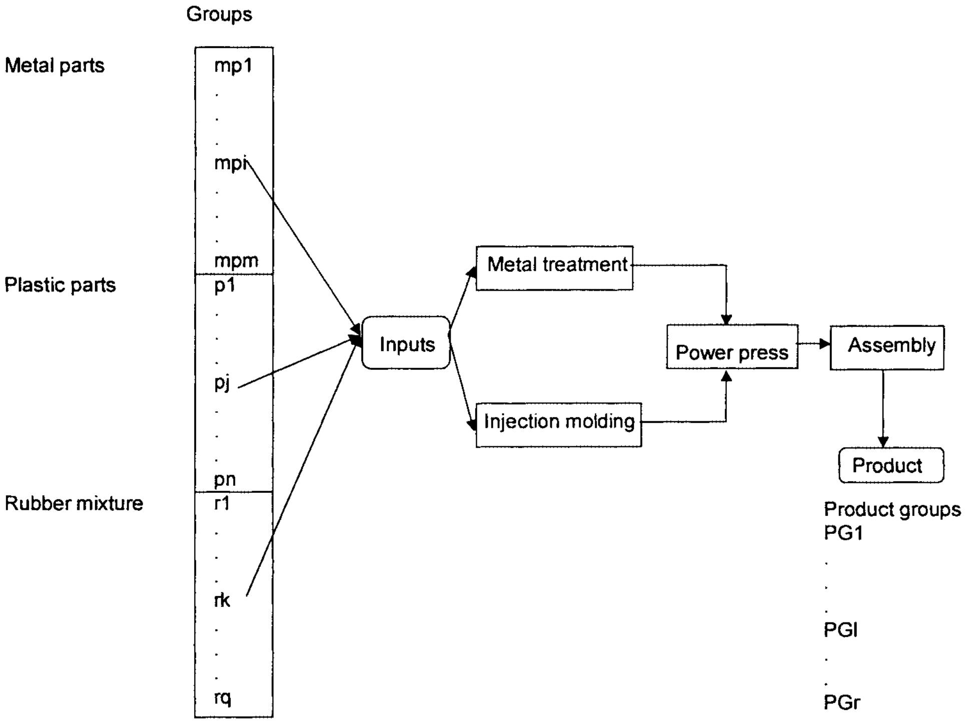
Groups
Metal parts
mp1
mpi
mpm
Plastic parts
p1
pj
pn
Rubber mixture
r1
rk
rq
Inputs
Metal treatment
Injection molding
Power press
Assembly
Product
Product groups
PG1
PGl
PGr

FIGURE 8.5.2 Model for group technology.

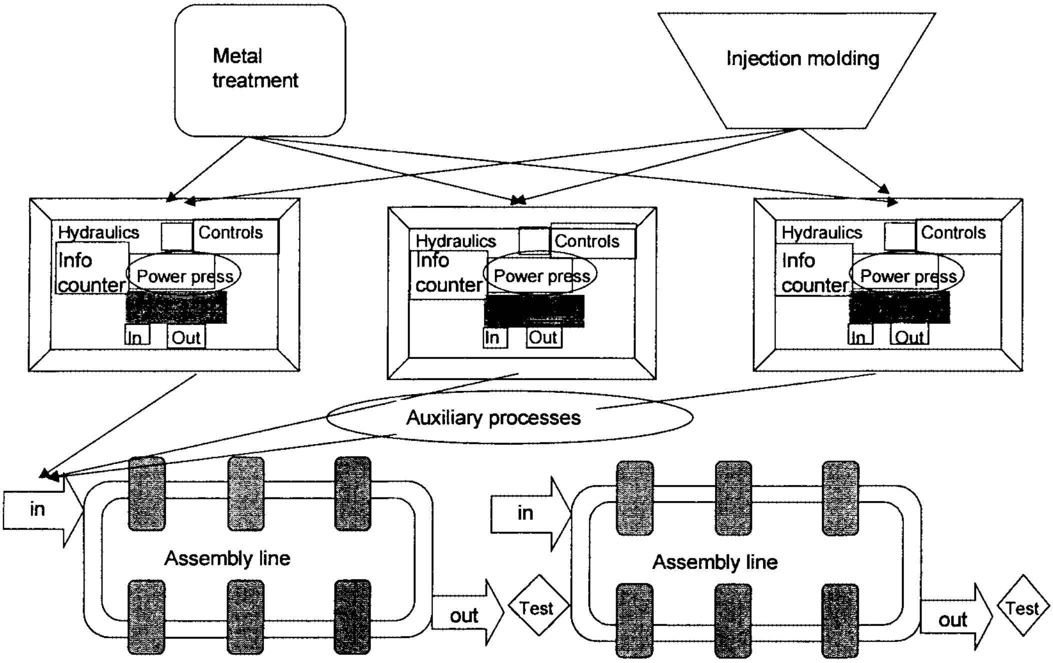

FIGURE 8.5.3 Technical representation of the group technology principles.

Considering that a fractal is an aggregate of identical or similar manufacturing and service processes and is serviced by workers, then a plant of fractals can be laid out (see Fig. 8.5.4). First, a temporary layout is made using the scissors-added design (SAD) method, in which the old design is cut up and several new designs are created. The final design is then drawn with the help of a CAD system.

It should also be noted that every workplace is connected to the information board, which contains the following items with respect to preparations and adjustments: establishing order of priority, balancing orders, and establishing product lot sizes. Directions for the machines and processes, pressure control, speed control, plasticity control, mold filling, and process times are also provided. The information board was the focal point for the relocation of the plants, the design of the plant of fractals, the instruction of the workers, and the application of MOST and SPA.

After the completion of the layout models, MOST analyses were conducted. They showed that, in many cases, the variances between the best and worst cases expressed in time values, time measurement units (TMUs), were too large. The MOST time values were positioned in the range 0.6 to 0.8 compared to stopwatch studies.

The SPA methods were first applied to the overall capability analysis. Benchmarks provided process capability indexes, C_{pk}, in the interval from 0.2 to 1.5, and product capability indexes in the interval from 0.1 to 2.7. These results indicated that many processes were out of control, and that for many products, the quality was poor. Therefore, if the capability indexes are less than 1, then other SPA methods have to be used.

For instance, a new specification of all relevant customer requirements could be used and/or an improvement of the processes in the network could be made. The process equation can be used for the control of the processes with the nominal values as targets to reduce the variability of all product parameters, or to balance the processes so that the mean and nominal values of the relevant product parameters are similar. An improvement of the communi-

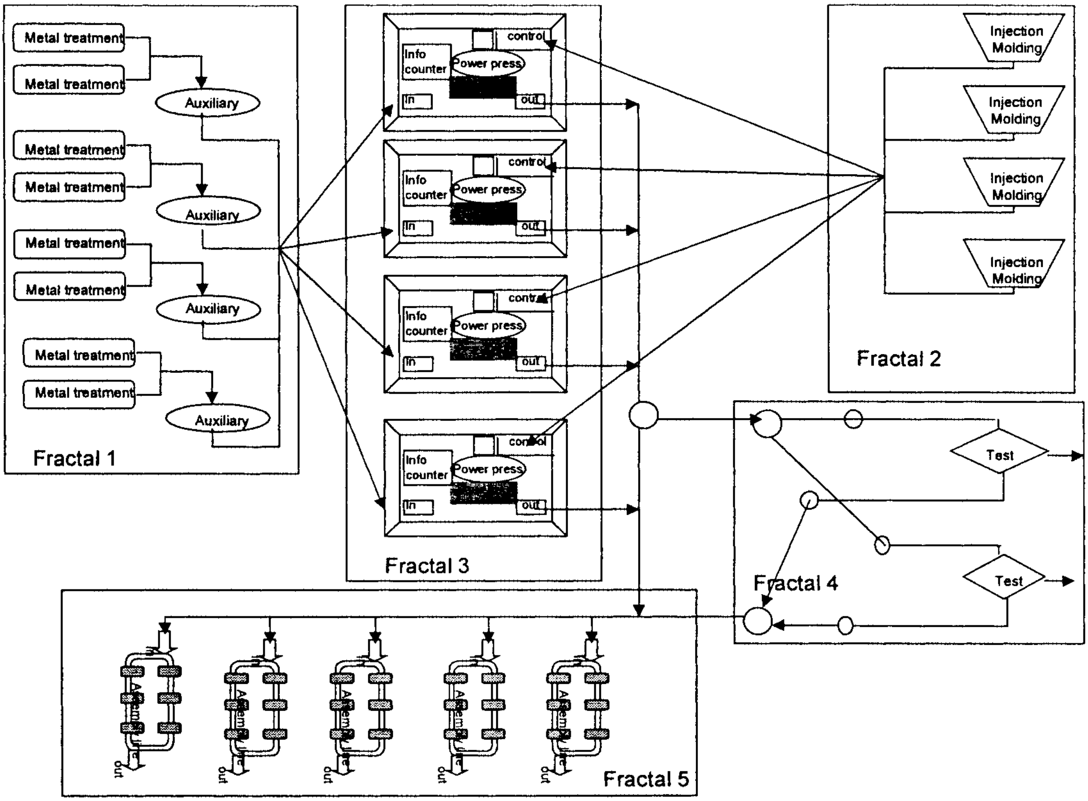

FIGURE 8.5.4 Plant of fractals.

cation between the processes and the external supplier and customer, and the transition from the hierarchical to a process-oriented organizational structure are alternative methods.

For some representative products in SP3 and SMU 1 designated as benchmarks, the nominal values and tolerance limits have been calculated for all relevant product parameters using the product equation. The processes were controlled with the nominal values as targets. The new process and product capability indexes are now larger than 1.3.

On the basis of the process and product capability indexes, the necessary decisions can be found in Fig. 14.3.4 in Chap. 14.3.

An analysis of the costs was done by the industrial engineering, the specialist, and the SPA teams.

In all studies, the topic of *cost* is ambiguous, because there are many country-specific factors related to costs. The definition of *cost* is not completely conclusive. We define costs as the financial assessment of the necessary consumption of working time in the processes, with special emphasis on labor, machines, material, and energy. "Necessary consumption" means that the cost function has to be optimized based on several conditions. The costs have to be determined as a function of several parameters: the capability indexes, the measures for the control of the processes, and the organizational structure.

The reduction of the costs can be realized through the reduction of labor costs or the necessary consumption of resources, or process improvement resulting in an increase of the capability indexes. The calculation of the costs can be done using the SPA methods. A rough analysis of the costs revealed that approximately 70 percent of all expenditures fall under material costs.

Material productivity ranges around 80 percent, since the purchasing department is price-oriented instead of quality-oriented. The improvement potential is approximately 10 percent.

Using SPA and MOST, potentially 25 to 40 percent improvement can be projected through the improvement of products, processes, and methods, as well as through the relocation of the plants.

Capital costs are the result of a break-even analysis. Because an estimated 70 percent of the capital costs were in the amortization category, the age of the equipment in the factories could be determined. In planning the new factory, 10 new investment projects were specified.

IMPLEMENTATION OF CHANGES AND IMPROVEMENTS

Relocation Plan

The relocation plan was completed ahead of schedule. The relocation of plants A, B, and C to the new plant C′ was finished 22 months after the start of the project, including all necessary activities such as the reengineering, SPA, and MOST efforts.

Transfer and Installation of Equipment

All vital machines were overhauled, relocated, and installed in accordance with the new C′ plant layout representing a plant of fractals. The environmental and security requirements were checked and adapted to the new conditions. The infrastructure of the supply network of energy, water, and gas was replaced. The information system including data management, product and benchmark catalogs, and the like was improved.

Evaluation of the New Processes

The network of manufacturing and service processes in one selected benchmark fractal was improved, so the process and/or product capability indexes became greater than 1.3 and the measures for the control of the processes were greater than 80 percent. That means that the variability of the relevant product parameters was explained by the most important input and process parameters. For the communication between the fractals and within each fractal, the necessary instructions with specifications of all external and/or internal customer requirements, control of the processes, proof of the conformance to the relevant requirements, and data collection were developed.

Instruction and Support of the Operators

The process owners were trained in the collection of input, process, and product parameter data and the compilation of all customer requirements, subsequently compared to the customer requirement profiles.

The training also covered the specification of the customer requirement profiles through the calculation of the nominal values and tolerance limits for the relevant product parameters, using the product equations. Further topics were the control of the processes with the nominal values as targets, using the process equations, and the proof of the conformance to all relevant customer requirements, using process and/or product capability indexes. The workers were trained in the use of flow charts outlining their own processes, data collection, and application of simple statistical procedures. For instance, frequency histograms, summary statistics, control charts, including cause-effect diagrams for the search of the causes if measurements of the product parameters appeared outside the control limits, and the inspection of quality—particularly of their own work—were included.

CASE STUDY: RELOCATING AND CONSOLIDATING PLANT OPERATIONS

RESULTS AND FUTURE ACTIONS

Relocation Report Including Results Versus Objectives

The relocation report included important results regarding the main issues, some of which are summarized here.

Following a classification of all products in strategic management units and strategic business units, the portfolio analysis disclosed that only about 30 percent (or approximately 1200 different products) retain an 80 percent market share. These products in high demand were earmarked for production in the new plant C′. All other products, those in low demand and spare parts, were to be produced in a separate plant. The cost for producing products in the benchmark fractal was reduced by about 45 percent. Productivity increased to 85 percent from the previous 40 percent level. The quality can be measured and improved subsequent to an increase of the product capability indexes for the benchmark fractal from 0.6 to 1.4. The measure of control was close to 85 percent, which means that the process will be controlled. Based on selected group technology principles, the network of manufacturing and service processes was restructured for the benchmark fractal. The capacity requirement analysis showed that the number of workers previously engaged in the manufacturing processes in the three plants (830) was reduced by 200 to 630 and the number of service employees (470) by 240 to 230 in the new plant C′. The maintenance cost was reduced by about 25 percent. The entire project was completed two months ahead of schedule. For further results, see Table 8.5.5.

Benefits Achieved and Lessons Learned

The improved communication between the processes, the portfolio and cost analyses, the process improvement, and the training of the employees have shown long-term benefits for the fractals as well as for the relocated plants. There is, of course, a risk that the composition of the management team will change and that the lessons learned will be forgotten if the daily dealings with these new methods are interrupted.

TABLE 8.5.5 Results of the Relocation of Plants A, B, and C to C′

Plant	A	B	C	New C′
Sales, products ×1,000,000	13.6	61.6	84.8	160
Sales, million DM/year	61.7	48.8	159.5	270
Number of products in profit plan 1997	170	420	420	1010
Number of products in catalog	1200	2400	2400	6000
Product types in catalog	400	800	800	2000
Total area, m^2	100 000	80 000	220 000	400 000
a. Manufacturing area, m^2	10 000	10 000	20 000	40 000
After relocation, m^2	0	0	20 000	20 000
b. Service area, m^2	5 000	5 000	10 000	20 000
After relocation, m^2	0	0	10 000	10 000
Workers before relocation	220	510	570	1 300
a. manufacturing	140	320	370	830
b. service	80	190	200	470
Workers after relocation	0	0	0	860
a. manufacturing	0	0	0	630
b. service	0	0	0	230

CASE STUDY: RELOCATING AND CONSOLIDATING PLANT OPERATIONS

Overall Outcome of the Relocation

The greatest benefit for the company emanates from the productivity increase. Based on the increase from about 40 percent to approximately 85 percent in the benchmark fractal, an overall productivity increase of 80 to 90 percent for the remaining relocated products can be expected. Thereafter, productivity should continuously improve through ongoing use and refinement of the updated methods applied in the fractals.

Future Aspects and Actions

The three plants have been relocated into the new plant C′. However, the process improvements, enhanced communications, and cost analyses were completed for only one benchmark fractal. The completion of similar improvements and analyses in the other fractals remains to be done.

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BIOGRAPHIES

Walter Jahn received his education from the School of Forestry, Germany, and worked at the school until 1960. He studied mathematics from 1964 till 1968 and graduated as Dr. rer. nat in mathematics. Jahn worked at the University of Leipzig, Germany, as a university lecturer, scientist, and head of the department of mathematical statistics until 1993. He is the author of four scientific books and many scientific articles. Jahn has 30 years of experience in the research and application of multivariate statistical procedures. Since 1994, he has worked as a freelance consultant on field control in processes and improvement of processes as well as networks of processes using multivariate statistical procedures.

Willi Richter is the leader of the consulting group Richter & Partner. The functional experience of the group encompasses manufacturing, industrial engineering, process and product development, production transfer, and process improvement. Richter is Diplomwirtschaftsingenieur. He has special training in MOST and 30 years of experience in the application of MOST and the relocation of plants. He has worked on projects such as building a technical center for automobile tests and consolidation of plants.

Source: MAYNARD'S INDUSTRIAL ENGINEERING HANDBOOK

CHAPTER 8.6

CASE STUDY: CHANGING FROM A LINE TO A CELLULAR PRODUCTION SYSTEM

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The current trend toward greater product diversification in response to customer demand has resulted in more multiproduct, small-lot manufacturing. For this type of manufacturing to be done efficiently, flexibility—particularly the ability to respond quickly to changes in demand—has become essential. Cellular production systems offer this flexibility. In this chapter we will examine the types of cellular production and some of the key elements needed for success in implementing cellular systems, such as the development of multifunctional operators and the optimum allocation of operators and equipment. Then, through a case study of the implementation of cellular production at a large-screen TV factory, the actual steps of such a program are described: forming a project team, establishing objectives, involving various departments (such as product design and production control), and finally, evaluating and implementing ongoing improvements. Finally, some remaining issues are described. Further study is needed and more must be made to ensure that the use of cellular production systems reaches its potential in manufacturing industries.

PRESENT SITUATION OF CELLULAR PRODUCTION SYSTEMS

Why Consider Cellular Production?

The cellular production system itself is not necessarily a new technique or method. It was widely discussed and debated in industrial circles in the 1980s, and it was well understood that high productivity could be realized by implementing programs aimed at improving quality, cost, and delivery (Q, C, D) and aggressively increasing the degree of automation at the cell level. For example, at Fiat's Casino factory in Italy, established in the mid-1980s, the whole body fabrication and assembly areas were built according to this way of thinking, and they succeeded in securing a >40-percent rate of automation that is quite remarkable. But at the same time, with cellular-type production, several problems created barriers to achieving a high level of cell capacity across all cells, and this resulted in a situation that made it difficult for cellular production to be seriously considered by the industrial community because

- It was necessary to keep ample inventories as buffer stocks.
- Distribution (material flow) management and control were not easy.
- Standardization on the factory floor and systematization of information were not achieved in time.

With regard to assembly lines, which require many operators, the introduction of automation is difficult, and even today one would be hard pressed to point to a production method that is effective in achieving both flexibility and speed.

On the other hand, modern-day cellular systems are enabling important advances in production, primarily in assembly operations that are "conveyor-less." To respond to the market requirements for speed and flexibility, the use of cellular systems has focused on the assembly process closest to the market, with the objective of maximizing flexibility and speed. In other words, it was recognized that the cellular system offered the important element of providing a production system that could be synchronized with the market/customer demands.

Such a production system does not merely seek management efficiency. It elevates the position assigned to operators, who in the past were viewed as mere cost elements, and broadly opens up the scope of operator initiative in regard to work. It thus enables human operators to exercise their full capabilities. With cellular production, the work that an operator takes charge of is not just an element of a job that has been divided into small parts, but is the entire work effort—ultimately embodied in a functioning product. It may even be said that a condition for the evolution of manufacturing (the task of making things) is the ability to evaluate and understand the work as a whole.

In this way, the basic idea of the cellular production system is to trust the operators and empower them to exercise greater initiative. Through their work, operators themselves take responsibility, from thorough pursuit of quality to the checking and verification of product functionality. The foundation of this approach is the belief that if people are empowered, their capabilities can be utilized to a maximum. Therefore, it is essential that multifunctionality is achieved. In that way, the operations of the total process can be self-integrated at the cell level. Needless to say, an important theme then is how to increase the understanding and skill of the operators to the necessary level.

Looking at the situation in Japan, the deterioration of the domestic economy since 1991 caused increasing interest in cellular production as a means for improving productivity in assembly-type manufacturing. This interest primarily centered around the consumer electronics industry, thereby increasing profitability and restoring competitive power in the international market.

In the past, the basic production method used in such industries was the straight-line production line method typified by conveyer lines. This approach was efficient in times when both the volume and variety of products were increasing (i.e., multiproduct mass production). However, in the present situation with no growth, or perhaps even a decrease in volume, but with no accompanying decrease (in fact, actually an increase) in the variety of products, many problems exist with the production systems of the past. This is because of the emphasis those systems placed on volume production. Under the present economic situation, conventional manufacturing methods have significant drawbacks with regard to the key factors of cost, quality, and speed. Those drawbacks include:

- The inability to respond quickly to changes and fluctuations.
- The number of operators cannot be reduced in proportion to a production slowdown.
- Losses from imbalances in the line itself may be large.

In addition, in the past, as the increase in the production volume proceeded, factories lost their sensitivity to changes in customer requirements. With the production systems of the past it was difficult to feel any direct connection with the customer, and as daily work became divided into more specialized tasks due to the volume increase, direct relationships with cus-

CASE STUDY: CHANGING FROM A LINE TO A CELLULAR PRODUCTION SYSTEM

tomers were lost entirely. Therefore, a review of production systems and a return to the fundamental aspects of manufacturing are needed. Those include

- Manufacturing that can share the satisfaction of customers
- Manufacturing whereby operators actually understand what kind of products the company is offering
- Manufacturing that understands its contribution to the business as a whole

Classification of Cellular Production Systems

If we trace back the origin of cellular production, most would agree that its original form is found in the U-shaped lines of Toyota, which reflected the concepts of "one operator/multiple machines" and "one-piece flow." The availability of cross-trained, multiskilled operators is a prerequisite for this method, and improvement of productivity becomes possible through the elimination of waiting time. By using the Toyota method, an operator loads one workpiece on the first machine and starts its operation, then moves to the next piece of equipment, loads the work on it, and starts it. After this is repeated successively, the operator returns to the first machine, just as it has finished processing the work, and can begin processing the next workpiece immediately. This is truly a perfect matching of people and equipment.

Currently, cellular production systems have been adopted for both fabrication and assembly processes, and the following characteristics are common to both of them:

- Integrated processing is sought for each product.
- People, tools, equipment, and materials are arranged according to the process sequence.
- Human operations and the movement of objects are done in parallel.

Cellular production systems are generally classified as follows:

- One-person scheme—assign one cell to one person.
- Rotation scheme—one cell is shared by several operators who move from station to station at approximately the same pace.
- Allocation scheme—the various process steps within the cell are divided up and work is accomplished through synchronized efforts of the cell team.

Structure of Cellular Production Systems: Way of Thinking and Basic Requirements

The cellular production system is a production system that, in a multiproduct manufacturing environment, can respond to fluctuations in the demand for each product type. It can be applied to increase total business efficiency, first by increasing productivity through making the products that can be sold, at the time they can be sold, and in the amounts they can be sold, and additionally by reducing inventories and increasing opportunities for sales.

For this reason, when a cellular production system is actually introduced, it is incorrect to emphasize only production efficiency and limit the application of the system to only the production area. To experience the maximum effect of cellular production, it is essential that all departments of the factory work together and cooperate in its implementation. In specific terms, the following measures are necessary:

- Create a sales and manufacturing structure that, through cellular production, can be systematized and synchronized with demand.

- In the product design area, review the design process so that ease of manufacturing is addressed, as well as standardization and common usage of components.
- From the viewpoint of industrial engineering, pursue reduction in equipment size and greater use of efficient layouts.

The two key elements for creating a cellular manufacturing system are (1) to integrate all activities of the company, from sales to product development and production through the application of cellular production and (2) to build a total company system such that all company activities can be synchronized to changes and fluctuations in the market, based on a "direct pipeline" to the market and customers. Figure 8.6.1 shows how developing each of these areas creates the foundation for an effective cellular manufacturing system.

Process Integration. A unique aspect of the cellular production system in contrast to conventional production systems is that it enables production to be directly linked to the market. In this context, process integration is essential, permitting production that responds agilely and promptly to changes in market requirements. Needless to say, the concept of process integration contradicts conventional supply-oriented (push-type) manufacturing and conveyor approaches, with their division of labor, which are considered efficient production systems for such manufacturing. Process integration instead focuses on having operators build the complete product or a whole functional part of it, either as a team or individually.

With process integration, the operator does not simply handle one tiny element of work, but takes responsibility for the entire operation and its completion. Consequently, operators clearly understand the meaning of the work they are doing and enjoy a strong feeling of achievement, which also has a positive effect. Production systems designed for large-volume production of a limited number of product models generally use conveyor-type lines. However, even when faced with a situation of multiproduct, small-lot production, many people engaged in production engineering still cling to the mentality that conveyer-type production is the proper model for all assembly lines. In contrast, the Toyota method, by adopting U-line production, has for many years been used to achieve process integration in the form of one-piece flow production, from fabrication operations through work completion. In regard to work area layout, process integration in cellular production systems, designed for quick response to changes in market requirements, is the same as U-line production. The basic concept of cellular systems is that finished products are completed by individual operators, with the objective of quick, essentially simultaneous response to the multitude of customer requirements that result from the trend toward greater product variety.

Process integration in cellular production systems is worthy of study because it offers a work system that routinely follows fluctuations in the market, enables production to be synchronized with the market, and provides a structure for self-completion of work based on operator control.

Optimization of People and Equipment. The basis of cellular production system is manufacturing that is directly interlinked with the market, and to achieve this, the thinking is: "Make what has been sold, when it has been sold, in the quantity that has been sold."

To realize this idea, an important prerequisite is to achieve the maximum level of flexibility, based on the capabilities of the operators, particularly their ability to adapt and make judgments in response to changes. However, in doing this, if distressful or difficult operations are forced onto operators, the result will be a negative impact on competitiveness. To achieve manufacturing that is connected directly to the market and has outstanding competitive strength, pursuit of high productivity must be a key element. In the present economic situation where demand is weak and product sales slow, the pros and cons of the mass production techniques of the past are debated and the drawbacks of conventional production systems are being revealed. Although it is true that cellular production systems result in higher productivity in many companies, the discussion should not only compare cellular systems with the production systems of the past, which are difficult to adapt to today's realities. One must go

CASE STUDY: CHANGING FROM A LINE TO A CELLULAR PRODUCTION SYSTEM

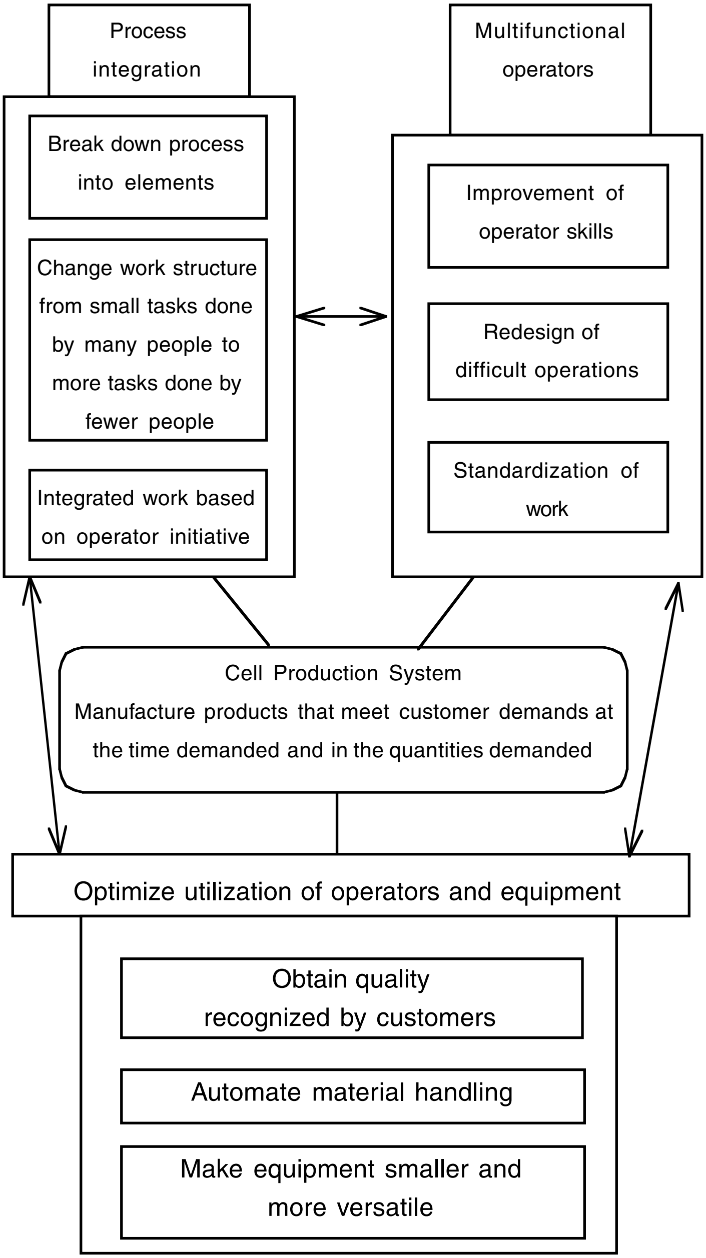

Process integration
Break down process into elements
Change work structure from small tasks done by many people to more tasks done by fewer people
Integrated work based on operator initiative
Multifunctional operators
Improvement of operator skills
Redesign of difficult operations
Standardization of work
Cell Production System
Manufacture products that meet customer demands at the time demanded and in the quantities demanded
Optimize utilization of operators and equipment
Obtain quality recognized by customers
Automate material handling
Make equipment smaller and more versatile

FIGURE 8.6.1 Basic concept of cell production system.

further and ask what *competitive power* really is in this era of global competition and what level of competitiveness is needed to survive. To effectively address optimization of people and equipment, these factors must be considered in a broad context.

In many cases, rather than reflecting on the production systems of the past, it would be preferable to return to a clean slate and reconstruct our thinking and systems. Specific areas where new thinking is required are described in the following sections.

Optimum Allocation of Labor and Equipment. The production systems of the past attached too much importance to investment efficiency and cost-performance, and it was obvious that those systems were not structured to make full use of the inherent capabilities of people. Instead, they often simply used human operators to cover areas that could not be automated.

However, major changes continue to occur in the labor environment, and even concerning cellular production systems there is a clear demand for a production system that is friendly to workers and places importance on individuals. What is such a production system? Let us consider it to be a production system that has as its basic principle to make full use of the inherent capabilities of people and enable them to display their creativity.

On the premise of converting to a production system that places importance on people, the general idea of changing the allocation of operations between humans and machines is shown in Fig. 8.6.2.

According to this figure, it seems that companies generally depend on people to perform tasks that are difficult, dirty, or require carrying heavy loads. However, in the production systems of the future, people will be allocated tasks that require mental work that can be done only by a person. Furthermore, to achieve this, automation and application of intelligent systems will be a key, and it becomes a role of industrial engineers to promote technological developments for that purpose.

Of course, even if we speak of automation as a simple, uniform subject, in each company the nature of the allocation of work between people and equipment will differ depending on the specific characteristics of the work performed. However, even after automation of machine operations, operations inappropriate for people often remain as manual (or human) operations. This may occur because of inappropriate "blocking" of production elements during the review and development stages, or unfavorable investment policies. The result is an imbalance in the allocation of work. Human operations should be considered in viewing the entire production process, not just its segments, and allocation should be made on the basis of assigning operators primarily self-managed, thought- or judgment-intensive operations.

A fundamental characteristic of cellular production systems is that they are people-centered; however, instead of focusing on manual operations, they seek a well-balanced distribution of work between operators and machines. Therefore, it should be pointed out that the objective of cellular systems is not merely to pursue a high percentage of equipment automation or faster cycle times.

To achieve a well-balanced allocation between people and equipment, it is essential to make the equipment smaller. However, in the current situation this topic has not been fully explored by industrial engineering departments and many aspects require further investigation.

Contribution of Operators to System Improvement. Recognizing that cellular systems place importance on the creativity of operators, it should be clear that the various system improvement activities, such as *kaizen*-type improvement programs, which result in effective system evolution over time, must be undertaken by the operators. Education and training play an important role here. Through study, operators gain new insights, which they then put to use in the next round of system improvements.

The Ideal Application of Human Operations. Cellular production removes the extremely monotonous and simple, repetitive operations of conventional systems and instead seeks to increase the professional ability of operators. As a result, human operations can be brought closer to their ideal, with work being done in an active and enthusiastic manner. However, if many difficult operations, such as carrying heavy objects, bending, stooping, or tasks requiring uncomfortable postures are required, the operators will become exhausted. As much as possible, such operations should be removed from the work of operators, either by only using equipment for those operations or by having equipment provide assistance or backup to the operator.

CASE STUDY: CHANGING FROM A LINE TO A CELLULAR PRODUCTION SYSTEM

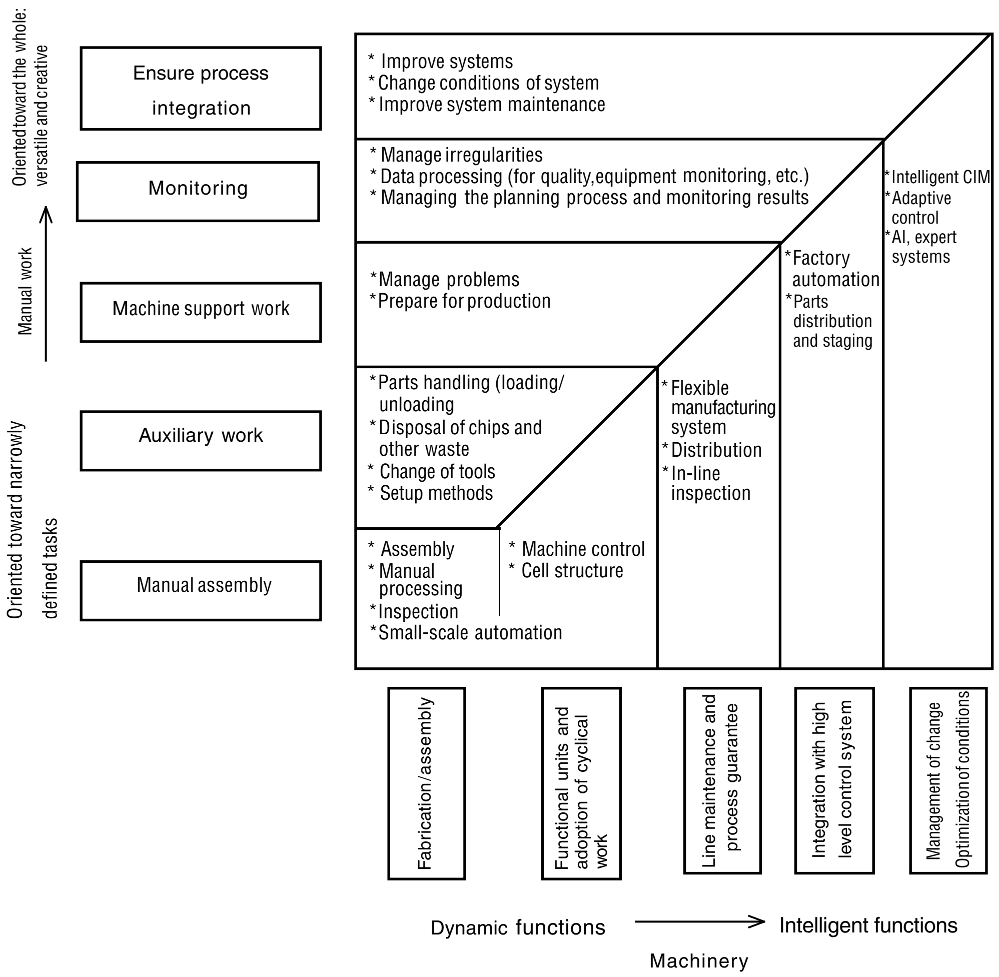

Oriented toward the whole: versatile and creative
Manual work
Oriented toward narrowly defined tasks
Ensure process integration
Monitoring
Machine support work
Auxiliary work
Manual assembly
* Improve systems
* Change conditions of system
* Improve system maintenance
* Manage irregularities
* Data processing (for quality, equipment monitoring, etc.)
* Managing the planning process and monitoring results
* Manage problems
* Prepare for production
* Parts handling (loading/unloading
* Disposal of chips and other waste
* Change of tools
* Setup methods
* Assembly
* Manual processing
* Inspection
* Small-scale automation
* Machine control
* Cell structure
* Flexible manufacturing system
* Distribution
* In-line inspection
* Factory automation
* Parts distribution and staging
* Intelligent CIM
* Adaptive control
* AI, expert systems
Fabrication/assembly
Functional units and adoption of cyclical work
Line maintenance and process guarantee
Integration with high level control system
Management of change Optimization of conditions
Dynamic functions
Intelligent functions
Machinery

FIGURE 8.6.2 Example of well-balanced allocation of people and equipment.

Developing Multifunctional Operators. Developing cross-trained, multifunctional operators is an important basic requisite of the cellular production system. It is an essential element of the process integration operating method that makes possible a structure that can respond efficiently to fluctuations in demand. It is a well-known fact that for years the Toyota production system in particular tended to develop multifunctional operators through job rotation (which was made possible through the use of standard operations).

To have a smoothly working system for developing multifunctional operators, the following aspects are prerequisites:

- Thorough standardization of operations and elimination of strenuous operations
- Active adoption of job rotation in an environment of mutual help and cooperation
- Improved layout of the equipment for the process to enable smooth flow

Once these prerequisites for developing multifunctional operators are in place, they need only to be implemented and continued to promote a systematic cross-training program to build up operator capabilities for various tasks.

In the case of cellular production systems, along with conventional programs for the development of multifunctional operators, the following few points need to be examined concurrently.

Review of Product Design from the Standpoint of Ease of Manufacturing (Design for Manufacturing). Since a basic assumption in the design of parts and components is that manual operations will be done with dexterity, the quality of assembly operations ultimately depends largely on the skill level of each operator. However, as operators are required to perform more and more different functions, there is a risk that they may not be skilled in all of them, and quality may deteriorate. Therefore, if the program of developing and using multifunctional operators is to be effective on the factory floor, it is essential to review the design of parts (their structure, design specifications, and tolerances) with the goal of making it easy for any operator to assemble them in the factory setting.

Self-Management of Parts Placement and Control by Operators. With the cellular production system, the parts delivery and placement activities for each process are complicated and demanding. Therefore, in this system, the operator performs the setup and changeover functions (receiving, stocking at each workstation, and drawing for use) for the parts used in the operations completed in that cell. In this way operators acquire information related to the products and production methods and improve their skills. This gain in knowledge, which extends even to management and control functions, results in operators who truly become broadly multifunctional. This approach is quite different from conventional attempts to achieve multifunctionality.

Feedback of Production Results and Promotion of Improvement Activities. The actual situation at most factories is that many people are busy dealing with problems that occur irregularly such as defective products, products requiring rework, equipment breakdowns, idle time, parts shortages, and schedule delays. However, the foundation of any program for improving the factory situation, regardless of the type of production system, is to find the exact root of the problems, plan effective corrective actions, and ensure that the same problems do not occur again.

Cellular production systems are effective in promoting improvements because, unlike earlier attempts at developing multifunctional operators, cellular systems require a broad commitment to *kaizen*-type activities, going far beyond the usual activities of finding waste and losses in operations and eliminating them. It is necessary for operators to be deeply involved in a factorywide improvement program addressing the design of parts and components, product quality, and production equipment and facilities. In particular, providing prompt and accurate feedback to the factory staff regarding criteria for their improvement-oriented reviews of parts, quality, and equipment is an important contribution that operators make in the process of improvement. A structure in which the improvement team (often a cross-department group) works closely with operators in a total operational review will lead to enhancement of productivity. Figure 8.6.3 shows how, in addition to reviewing the conventional elements of parts, quality, and equipment, informational elements such as "foolproof design" and design for manufacturability must also be considered in an effective operational review.

INTRODUCING A CELLULAR PRODUCTION SYSTEM: THE CASE OF A CONSUMER ELECTRONICS MANUFACTURING COMPANY

The Purpose and Objectives of Introducing Cellular Systems

The purpose of introducing cellular production systems and the targeted objectives will vary according to the situation of each company, but generally, the purpose is to shorten lead time, reduce inventory, and enhance productivity.

We will examine these points in the context of a case study of the consumer electronics manufacturer LG Electronics' TV manufacturing division.

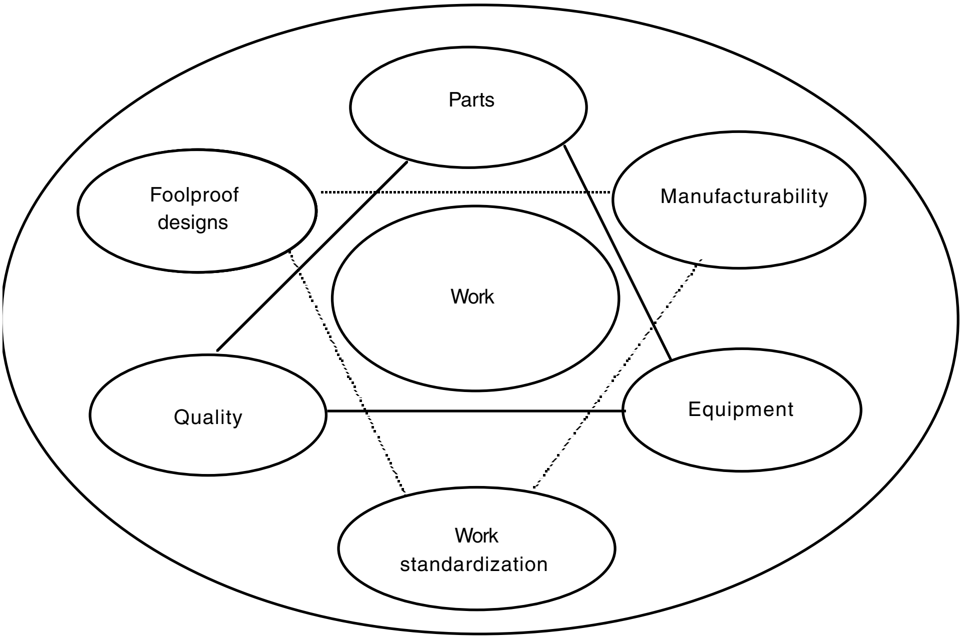


FIGURE 8.6.3 Total review of operational issues.

The Product—Large-Screen TV Sets for Home Use

Number of models produced	50 or more
Lot size	50–200 units, on average
Factory capacity	1000 units per shift

Limitations of the Current Production System. At LG Electronics, the assembly process for large-screen TVs consists of a mixture of manual lines and automated lines. The entire production process is divided into four subprocesses set up in an in-line process line.

1. Cabinet assembly process
2. "Burn-in" process
3. Adjustment process
4. Packaging process

(In practice, a total of 35 process steps are performed within the four subprocesses.)

The following problems existed due to the nature of the in-line production system:

- Productivity declines because of the frequent model changes (multiproduct, small-lot sizes) in response to changes in the market.
- A flexible configuration that meets fluctuations in demand cannot be formed.
- As a result of not being able to respond promptly to changes and fluctuations in the market, inventory levels increase and overall business efficiency drops.

Cellular Production Systems: Fundamental Thinking and Objectives. The following is a summary of the fundamental concepts of a cellular production system:

- Produce only the products that can sell, at the times they can be sold, and in the quantities that can be sold.
- Focus on productivity improvements by addressing the complete assembly process.
- Respond efficiently to changes in product specifications and fluctuations in production volume.

In the case of LG Electronics, those basic concepts were expressed as firm objectives for achievement as follows:

Gross business lead time (from order receipt to production/shipping)	reduce by 75 percent
Gross production cost	30 percent reduction (including reduction of parts costs)
Total inventory	reduce by 50 percent

However, large-screen TV sets have a maximum weight of 60 kg, the number of process steps is large, and a high level of operator skill is required. For these reasons, there was concern as to whether cellular production could be implemented in this situation.

Project Structure for Managing Introduction

In the actual example of cellular production system for large-screen TV sets at LG Electronics, there was also the goal of significantly reducing production cost. Therefore, with the introduction of the system, the following actions were taken:

- The design of all parts was reviewed.
- Efforts were made toward greater standardization.
- Design for manufacturability was pursued.

In addition, along with rebuilding the production control system to create a total system that enables coordination with sales, the information systems were reviewed and rebuilt to permit management and control of the factory to be done in real time.

To provide leadership in introducing these changes at LG Electronics, a dedicated project team was organized. Such a team should be organized by

- Selecting a leader from the manufacturing section in which the cellular production system is to be introduced
- Structuring the project so that the support of other sections—design, industrial engineering, and production control—is obtained without complication
- Facilitating the implementation and lateral expansion throughout the factory, establishing a flexible team structure that has rotating membership appropriate to each task and includes the participation of operators from the relevant factory area

Figure 8.6.4 shows how a cross-discipline project team, composed of members from all involved departments and cooperating closely with the factory personnel, is essential to design and manage the process of conversion to cellular production.

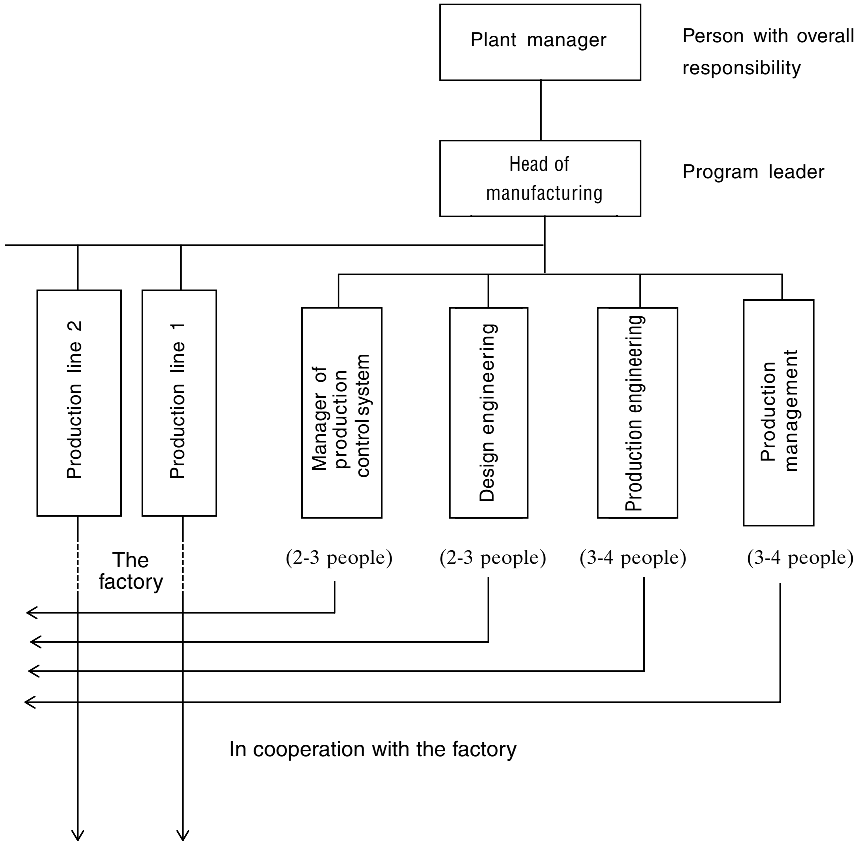

Plant manager
Person with overall responsibility
Head of manufacturing
Program leader
Production line 2
Production line 1
Manager of production control system
Design engineering
Production engineering
Production management
The factory
(2-3 people)
(2-3 people)
(3-4 people)
(3-4 people)
In cooperation with the factory

FIGURE 8.6.4 Team composition for a cell production promotion program.

Procedures and Tools for Expanding the Use of Cellular Production Systems

In designing and introducing cellular production systems, it is important to take an overall view and consider people, parts and components, equipment, and information.

In Fig. 8.6.5, the steps for rolling out a cellular production system are shown. It is important to (1) build up, step-by-step, the design for conversion to cellular production, and at the same time, (2) at each step of the design, thoroughly eliminate waste and losses associated with the current production methods.

Step 1. Defining the Target Conditions. The judgment of whether the product line under consideration is suited for cellular production is difficult to make. A situation where the sales volume of each model of the product line does not grow, and yet the number of models continues to increase, generally indicates that introduction of a cellular production system is worth considering.

The production lot size for each model should be set as the target production volume of that model in a cellular production situation. The lot size for each model will of course fluctuate and that can be accommodated by a change in the production time or in the number of operators assigned.

Improvements can be expected mainly in the areas of productivity, lead time, and quality, and in some cases, results may extend to reduction of total cost, shortening of business lead times, and improvement of customer satisfaction.

Step 2. Determination of Process Steps in the Cell. The work area layout will be made according to the process steps for the given product, and it is desirable to condense the process steps so that a block of related functions becomes one process step. By doing this, it becomes easy to pursue quality issues intensively in each process step, and if needed, recommendations on improvements in product design for easier manufacturability can be sent back to the design department from the manufacturing team.

The segmenting and arrangement of cells can be done according to the three cell-organization schemes mentioned previously: one-person scheme, rotation scheme, or allocation scheme. To transfer the product between stations or cells, generally the two methods of manual transfer or cart transfer are considered.

Step 3. Design of Operations. Once the process steps for the cell are determined, the range of the flow path for operations will become clear, and we can begin to consider operating procedures and cycle times according to the desired throughput.

In cellular production systems, the span of time designated as the cycle time is typically much longer than the cycle time of a conventional line-type production system. A benefit then is that the variations in the short cycle times that cause losses under line systems now become essentially absorbed, since a series of those short cycle times now makes up one cycle in the cellular production situation. However, waiting time losses due to differences in operator experience and skill are still possible. To avoid them, flexibility must be built in at the time of the design of the operation.

An important task in operation design is to accurately expose any losses within the process steps or variations (imbalance) in operation times throughout the entire production cell and eliminate or reduce them. While pursuing overall operation efficiency, it is also important to return to the design stage and actively try to improve the operability (ease of work accomplishment) in the cell as well as the ease of manufacture of the product itself.

Step 4. Optimize the Allocation of People and Equipment. To increase overall productivity and quality, it is important to consider the most suitable allocation of operations to operators and machines. In designating work to be done by operators, one requirement is that these be easy operations, not requiring excessive effort. In contrast, the following operations are some that should be assigned to equipment.

- Changing the position of workpieces, such as rotating or turning over heavy workpieces
- Handling heavy workpieces
- Fabricating or processing of workpieces
- Testing the product

In selecting which operations should be done by operators and which by machines, it is important to consider using human capabilities to the maximum and thereby increasing total production efficiency.

Step 5. Designing the Management and Control Systems. In shifting to a cellular production system, the production control system will usually need a major upgrade. Changing to short production runs is a key element of cellular production. Every day each product model may be produced, and therefore the system for daily scheduling of work assignments and instructions must be changed significantly from the system of the past. Above all, the situation should be reviewed and changes should be made with the objective of creating a production control system that can be synchronized with sales information. In the LG Electronics case,

Steps	Action	Detailed actions	Feedback to product design	Elimination of waste factors
1	Establish target conditions.	• Determine expected conditions and results. • Optimize production lot size based on the products that can be sold, in the amounts that can be sold.		Waste from overproduction
2	Determine the process steps.	• Set the standard process steps. • Set up the cell units and allocate the work.	• Reduce number of parts. • Standardization of parts and common usage.	• Waste in operations • Waste in the pick and place steps
3	Design the work.	• Organize the human power allocation. • Set the work flow path and range.	Design to ensure Q, C, and D.	Waiting time losses
4	Design work allocation (i.e., allocate optimally to operators and/or machines).	• Set standards for quality inspections. • Make handling easier. • Evaluate the interaction of manual and machine work. • Design improved equipment, jigs, and fixtures.	Design for ease of manufacturability: • Eliminate difficult work. • Simplify work so it can be done by anyone. • Eliminate need for checking. • Make handling easier.	• Waste from walking • Waste in other actions and motions • Waiting time losses
5	Design the management control system.	• Set a basic philosophy for design and production. • Monitor conversion to new methods. • Confirm results. • Revise work instructions.		• Losses from excesses of people, equipment, or time • Waste due to changes • Waste due to variations in production volume
6	Design the distribution (parts flow) system.	• Optimize parts flow within and between processes. • Design improved parts supply, parts staging system.	Optimize parts flow design aiming for • Ease of staging. • Increased storage efficiency. • Stability in transit. • Ease of identifying and picking out parts.	• Waste in WIP, space, and transportation
7	Design the operations.	• Set inventory standards and implement control system. • Control movement of items to/from the factory floor. • Manage parts receiving. • Plan for achieving multifunctionality.		
8	Evaluate the overall system.	• Evaluate results in comparison to targets. • Implement rollout of plan. • Design review.		Smooth flow of manual operations Operations done closer to parts staging points Reductions in waste due to • Waiting or idle time • Defective products • Rework

Procedures and tools for expanding the use of cellular production systems.

based on this principle, the scope of discretion given to the production control department in determining work assignment schedules was considerably broadened.

Step 6. Designing the Distribution System. When converting to a cellular production system, complications in staging and supplying parts may cause problems. In some cases the operator must play an active role, for example when the supply base for staging parts is placed near the work area and the operator must select the parts him- or herself.

Step 7. Designing the Operation of the Cell. In introducing cellular production, most companies take a step-by-step approach, with the new production method being introduced into factory areas one at a time. One reason for this is that changes must be implemented in step with the understanding, acceptance, and motivation of the operators in regard to cellular production. Particularly, it takes time to achieve the ideal of multifunctional operators through training and increased experience. In this regard, constant evaluation of operator work and the use of charts of the functional qualifications of each operator can be valuable tools for speeding up the successful adoption of cellular production.

Even though efforts were made to eliminate losses in each process step, during the early stages of operation of the new cellular system many losses still remain here and there, including "pick and place" losses and losses due to operator waiting time. To eliminate these losses, strong perseverance and repeated improvement activities are needed.

Step 8. Overall Evaluation. If switching to cellular production can be done based on the understanding and agreement of operators, then improvements can be made in many areas, including productivity, quality, and (inventory) lead time, compared with the present situation, and outstanding results can be obtained. It is vital to evaluate the results and compare them to the initial objectives, and following such an analysis, to continue the untiring efforts toward further improvements.

Figure 8.6.5 shows the procedure for expanding the use of cellular production systems, once their viability has been demonstrated in a certain application. At each stage, action is taken and for each action, output is generated, such as instructions and standards. In addition, wherever needed, feedback is provided to the product design group so that future products can be designed to better facilitate cellular production. Finally, attention is always given to ways of reducing waste, and this is done systematically as part of the procedure for rolling out the use of cellular production.

Changes and Improvements That Accompany the Introduction of a Cellular Production System

In the case of the large-screen TV assembly process of LG Electronics, the 35 process steps were previously handled by around 40 people, but with the adoption of a cellular production system the number of process steps was condensed to 3, and staffing was also reduced to 3, as shown in Fig. 8.6.6.

However, large-screen TVs have inherently a large number of parts and their unit weight is heavy (maximum 60 kg). In TV production, the burn-in and adjustment process steps are critical to ensuring functionality and quality, but these processes have always required a lot of time and labor-hours. Therefore, at LG Electronics, the following changes and improvements were made.

- Parts were preassembled into units or subassemblies so that final assembly could be done more easily. To facilitate this, standardization of parts became important.
- Because of the heavy weight of the products, they could not be carried by hand, so the work area was changed to enable transfers on pallets. To make the adjustment operation easier, a mechanism for turning over the units was built in.

CASE STUDY: CHANGING FROM A LINE TO A CELLULAR PRODUCTION SYSTEM

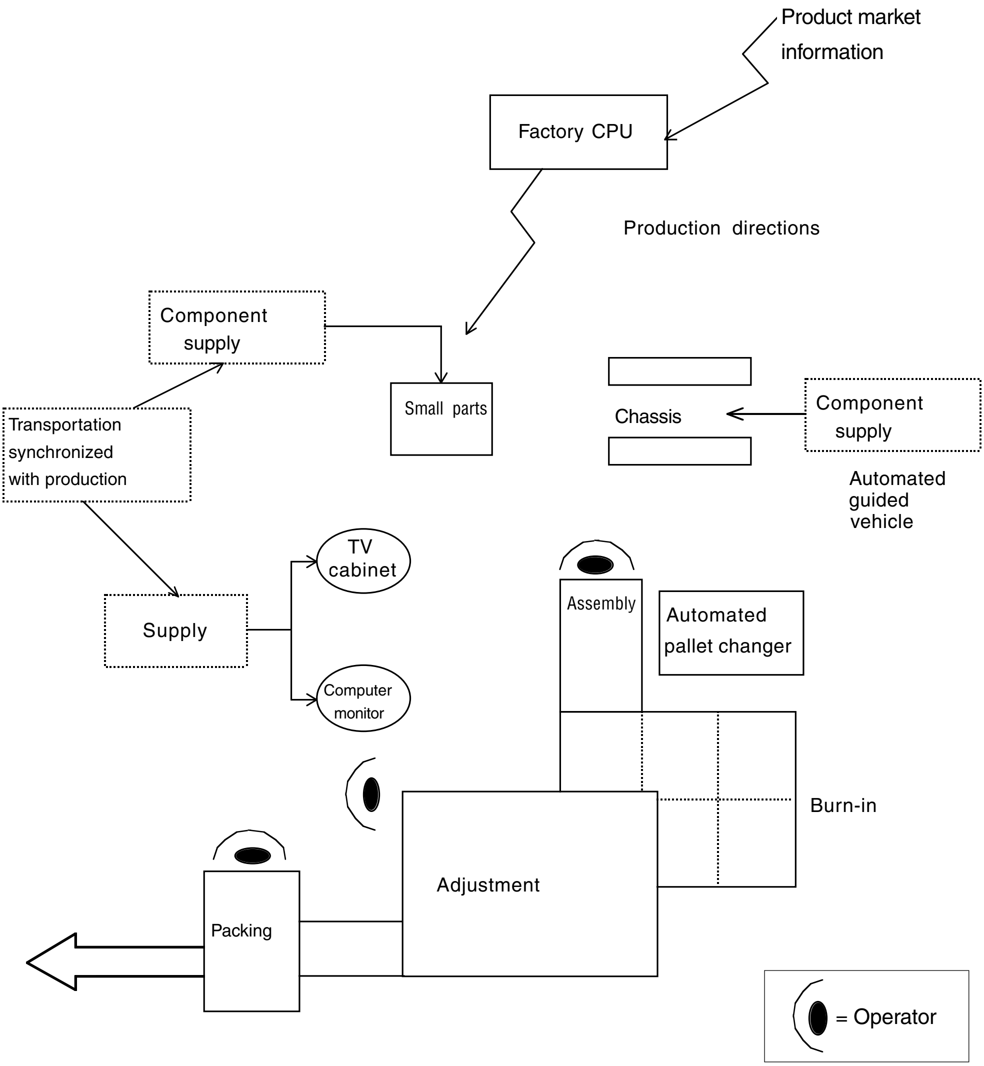

Product market information
Factory CPU
Production directions
Component supply
Small parts
Chassis
Component supply
Transportation synchronized with production
Automated guided vehicle
TV cabinet
Supply
Computer monitor
Assembly
Automated pallet changer
Burn-in
Adjustment
Packing
= Operator

FIGURE 8.6.6 Overall structure of a cellular production system.

- Since the burn-in process takes the most time, a storage area was set up so that products could be burnt in while still stacked on pallets.
- The automatic measuring instruments required in the adjustment step are expensive, and at the time when cellular production was introduced, small, simple, low-cost measuring instruments were not available. Therefore, complete automation of the adjustment operation was not done. However, even though manual adjustment continued to be used, it became clear that the quality was actually improved, since operators were trained to consider the perspective of the customers and their expectations.

At LG Electronics, through these improvements and other measures, production parameters could be established as follows:

Cycle time	40 minutes
Number of operators per cell	3 people

The objective here was not a mere reduction in total number of operators. The productivity improvements according to traditional measures are listed in the next section, but in addition, strategic improvements were achieved, such as

- A reduction in losses from line changeovers
- The ability to respond quickly to changes in market trends

Results of the Introduction and Topics for Further Study

Through the realization of a cellular production system for large-screen TVs at LG Electronics, it was demonstrated that cellular production systems could be effective even for heavyweight, large-sized products. Also, considering the original target objectives, the following results have already been achieved, or soon will be.

General productivity of assembly process	improved to 1.5 times the baseline
General business lead time	reduced by 75 percent (including the impact of conversion from monthly to weekly production cycles)
Total production cost	reduced by 30 percent (includes the impact of the redesign of parts)

There remain some topics for future study that may lead to further improvements. These include

- Improved parts design, greater parts standardization, reduction in parts count, and increased common usage of the parts
- Simplification of production processes

One of the keys to success of this project, particularly in achieving the 30-percent reduction in total production cost, was the use of the variety reduction program (VRP) design technique developed by JMA Consultants, Inc. It provided a new way of reviewing the design process that had the dual objectives of converting to multiple models and standardizing parts (especially standardizing the electronic parts of the chassis). The results were a significant reduction in parts count, an increase in common usage of parts, and simplification of the production process. The VRP design technique has already been introduced in many assembly-type companies, with positive results.

Furthermore, the production planning/scheduling cycle was reduced from monthly to weekly, and the production control system was examined and improved with a view toward synchronizing production and sales. This approach of putting in place all the conditions necessary for full-scale adoption of cellular production systems is very effective.

In introducing cellular production systems and then expanding their use with the objectives of reducing business lead time and production cost, the thoughts and methodology described previously should be valuable resources.

At the same time, the following issues remain.

- At LG Electronics, the trial layout and operation of the cellular production system was accomplished without difficulty since the available operators were quite capable. An issue

CASE STUDY: CHANGING FROM A LINE TO A CELLULAR PRODUCTION SYSTEM

that still remains is how to accomplish lateral expansion of cellular systems (rollout to other production areas) while at the same time training operators who are less qualified.

- Because this was a trial, or model line, it was decided to make adjustments manually. However, a major remaining issue in the area of equipment development is how to eliminate the large automatic measuring instrument that is presently used and replace it with a small, easy-to-use model, making it practical to allocate one instrument to each cell.
- The need for a support system to enable picking of parts, production control, and other functions to be done in real time at the discretion of the operators was also revealed.

A few other concerns remain, beyond these listed here. However, there is no doubt that cellular systems offer an effective new alternative to conventional production methods that focus only on efficiency and, with the trend toward multimodel product lines, have lost the ability to respond quickly to changes in the market. To promote cellular production systems, however, it is essential to continue to study and evaluate them from every angle, taking the broadest possible view.

Finally, let us review the benefits of adopting cellular production systems.

1. The cellular production system is an efficient system for responding quickly to demand fluctuations, in the context of multimodel product lines. By producing what can be sold, when it can be sold, in the amount that can be sold, improvement of the total business efficiency can be achieved, including not only improved productivity but also reduced inventory and increased opportunities for sales.
2. The cellular production system offers an effective means of achieving broad improvements. It is not right to regard it as simply focused on flexibility and production efficiency or as limited only to the manufacturing area. It is a system for bringing out the full potential of employees and, as such, has application throughout companies' functions.
3. By integrating the activities of the sales, product development, and production departments, and in effect building an information pipeline directly connected to customers and the market, a cellular production system becomes a companywide system enabling synchronization with changes and fluctuations in the market.

When determining whether to apply cellular production systems, these advantages should be recognized and given full consideration. A cellular production system should become a total production system, positively impacting many areas of the company.

BIOGRAPHY

Kazumi Eguchi is president of Idea, Inc., a Japanese management consulting company. In 1974 he received his master's degree from Keio University. After three years with an engineering company providing equipment design services to the nuclear power industry, he joined JMA Consultants, Inc. (JMAC) of Tokyo. His areas of specialization included product cost reduction, factory automation, and computer-integrated manufacturing (CIM). From 1989, he served as head of JMAC's CIM department, its development and technology department, and finally its equipment and quality engineering department. In 1997, he left JMAC to form his own company: Idea, Inc. He is the author of *Re-engineering Production Systems,* and coauthor of *FA Engineering* and *Procedures for Achieving 50% Cost Reductions.*

SECTION 9

FORECASTING, PLANNING, AND SCHEDULING

CHAPTER 9.1

AGILE PRODUCTION: DESIGN PRINCIPLES FOR HIGHLY ADAPTABLE SYSTEMS

Rick Dove
Paradigm Shift International
Questa, New Mexico

Highly adaptable (agile) production capability is enabled by an engineering design that facilitates the reconfiguration and reuse of common modules across a scalable production framework. Examples of agile fixtures, machines, cells, assembly lines, plants, and production organizations are presented; and a common set of 10 underlying design principles are shown to be responsible for the high adaptability in each. Finally, a method for capturing and displaying these principles in action, which facilitates learning, knowledge transfer, and competency development, is demonstrated.

INTRODUCING PRINCIPLES FOR AGILE SYSTEMS

In 1991 the author co-led an intense four-month-long collaborative workshop at Lehigh University that gave birth to the concept of the agile manufacturing enterprise. This workshop was funded by the U.S. government and engaged 15 representatives from a cross section of U.S. industry plus 1 person from government and 4 people as contributing facilitators. The Japanese had just rewritten the rules of competition with the introduction of lean manufacturing. Our intent was to identify the competitive focus that would be the successor to lean—believing that there would be value in building competency for the next wave rather than simply playing catch-up on the last.

The group converged on the fact that each of their organizations was feeling increasingly whipsawed by more frequent change in their business environments. The evidence was apparent that the pace of change was accelerating—and already outpacing the abilities of many established organizations. With even faster changes expected it became evident that survivors would be self-selected for their ability to keep up with continuous and unexpected change.

We dubbed this characteristic *agility* and loosely defined it as "the ability of an organization to thrive in a continuously changing, unpredictable business environment."

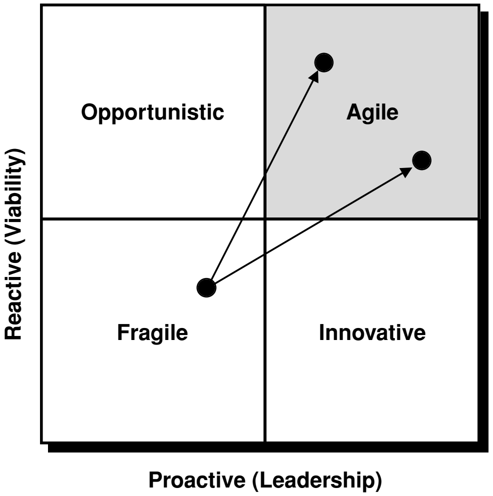
Being agile means being a master of change, and allows one to seize opportunity as well as initiate innovations. How agile your company or any of its constituent elements is, is a function of both opportunity management and innovation management—one brings robust viability and the other brings preemptive leadership. Having one without the other is not sufficient in these times of quickening unpredictable change. Having neither is a time bomb with a short fuse.

How much of each is needed at any time is a relative question—relative to the dynamics of the competitive operating environment. Though it is necessary to be only as agile as the competition, it can be extremely advantageous to be more agile.

All of this talk about "how agile" and "more agile" implies we can quantify the concept and compare similar elements for their degrees of agility. However, as Fig. 9.1.1 shows, there is some question about value trade-offs between an increment of leadership and an increment of viability.

- **Viability:** Seeks and responds to the voice of the customer, says yes to opportunity, is reactive and resilient, has staying power and robustness.
- **Leadership:** Introduces new approaches, makes existing approaches obsolete, changes the rules, promotes out-of-box thinking, disrupts the market.
- **Plot* any business element:** Enterprise competitive position, plant operation, supply chain strategy, specific shop-floor process, teaming strategy, product development, etc.

* See *Change Proficiency Maturity Model* at www.parshift.com for plotting techniques.



If You Could Move, Which Is the Better Move?

FIGURE 9.1.1 Agility space.

Leadership wins if the leader always chooses the most optimal path to advance, but one false step allows a competitor to seize the advantage—putting the previous leader in reaction mode. A competitor with excellent viability can track the leader, waiting for that sure-to-come mistake. Poor viability may then keep the fallen-from-grace ex-leader spending scarce resources on catch-up thereafter.

Choosing a desired spot in the agile quadrant is one of the important ways to strategically differentiate yourself from your competitors. Getting to your chosen spot is another issue entirely—and a job for masters at business engineering, not business administration.

How innovative/opportunistic are you—relative to your competitive needs and business environment? How fast are the rules changing in your market? Are you able to respond fast enough, can you introduce a few changes of your own? More important: What allows you to do that? We will look subsequently at some promising design principles to answer this question.

The search for metrics and analytical techniques that can pinpoint an enterprise in the agility space has received a lot of attention. Self-analysis tests that ask lists of questions are one form, house-of-quality QFD-like templates are another. These have a certain appeal because they deal with familiar concepts that enjoy intuitive association with agility: teaming, empowerment, partnering, short cycles, integrated process and product development, and so forth.

But experience shows us that simply saying yes to these questions will not tell us anything useful—too many people, for instance, will say yes to having empowered teams when the yesness has nothing to do with the quality of the implementation, or if the implementation promotes agility. Better to ask how well we respond to critical types of unexpected situations, how often we lead with a meaningful innovation, how proficient we are at a variety of identified changes we feel to be strategically important. For sure, empowered teams embody an organizational structure and business practice that can help us be more agile, but only when they are designed and supported with that end in mind.

There are tools that can identify the location of a company in agile space relative to its business environment and competitive realities [1]. When a company decides it is time to change its viability/leadership position it must select and design strategies that will move it to where it wants to be. The selection of appropriate strategies changes with the times and differs from market to market. In the early twenty-first century, appropriate strategies might include mass customization, virtual enterprise relationships, employee empowerment, outsourcing, supply chain management, commonizing production, or listening to your customer.

Strategic concepts by themselves are open to a wide range of interpretation, however, and are often interpreted incorrectly. Commonization in shop floor controls, for instance, does not pay agility dividends if it is interpreted as buying controls from one vendor; empowerment does not pay without an information and support infrastructure, and customer listening does not pay when competitors change the rules.

Key Definitions

System: A group of interacting modules sharing a common framework and serving a common purpose.

Framework: A set of standards constraining and enabling the interactions of compatible system modules.

Module: A system sub-unit with a defined and self-contained capability/purpose/identity, and capable of interaction with other modules.

Business strategists recognize the imperative of the agile enterprise, with virtually all popular business writers extolling the need for change proficiency of one kind or another. Of particular note is Richard D'Aveni's excellent book, *Hypercompetition* [2], which focuses on wielding change proficiency as a preemptive business strategy, and Kevin Kelly's *Out of Control* [3], which provides fundamental examples for the business engineer who would design and build agile enterprises and production systems.

Regardless of the strategies chosen, effective implementation employs a common set of fundamental design principles that promote proficiency at change.

Designing agile systems, whether they be entire enterprises or any of their critical elements like business practices, operating procedures, supply chain strategies, and production processes, means designing a sustainable proficiency at change into the very nature of the system. A business engineer is interested in both the statics and the dynamics of these systems—where the static part is the fundamental system architecture and the dynamic part is the day-to-day reengineering that reconfigures these systems as needed.

Sustaining a desired opportunistic/innovative profile is dependent on the agility of these systems, which in turn is impeded or enabled by their underlying architectures. In the next section we discuss reusable/reconfigurable/scalable (RRS) system strategies. Figure 9.1.2 provides a set of 10 design principles for these RRS systems. These principles have emerged from observations of both natural and manufactured systems that exhibit RRS characteristics, with contributions from the Agility Forum's 80-case Agile Practice Reference Base [4], Kevin Kelly's thought-provoking book [3], and the sizable body of knowledge and experience growing out of object-oriented systems design.

We will explore the application of these principles, tying them into various production strategies useful to the agile enterprise.

Any organization of interacting units is a system: an enterprise of business resources, a team of people, a cell of workstations, a contract of clauses, or a network of suppliers.

Self-contained units System composed of distinct, separable, self-sufficient units not intimately integrated.	Distributed control and information Units respond to objectives; decisions made at point of knowledge; data retained locally but accessible globally.
Plug compatibility System units share common interaction and interface standards, and are easily inserted or removed.	Self-organizing relationships Dynamic unit alliances and scheduling; open bidding; and other self-adapting behaviors.
Facilitated re-use Unit inventory management, modification tools, and designated maintenance responsibilities.	Flexible capacity Unrestricted unit populations that permit large increases and decreases in total unit population.
Nonhierarchical interaction Nonhierarchical direct negotiation, communication, and interaction among system units.	Unit redundancy Duplicate unit types or capabilities to provide capacity fluctuation options and fault tolerance.
Deferred commitment Relationships are transient when possible; fixed binding is postponed until immediately necessary.	Evolving standards Evolving open system framework capable of accommodating legacy, common, or completely new units.

FIGURE 9.1.2 RRS (reusable/reconfigurable/scalable) system principles.

AGILE MACHINES AND AGILE PRODUCTION

Agile production operations thrive under conditions that drive others out of business. When forecasts prove too optimistic or markets turn down, they throttle back on production rate with no effect on product margins. If product life ends prematurely, they are quickly reconfigured and retooled for new or different products. Instead of loosing market opportunity when product demand soars beyond capacity, they expand to meet the market. Rather than postpone or shut down periodically for major process change, they evolve incrementally with continuous incorporation of new process technologies. In support of new product programs, they freely take prototypes in the work flow. For niche markets and special orders, they accommodate small runs at large run margins. Irrespective of all of these changes, they maintain superior quality and a steady, loyal workforce.

Agile machines and agile operations also accommodate work flows of intermixed custom configured products—the mass customization concept frequently misunderstood as the defining characteristic of agile production. Mass customization is just one of many valuable change proficiencies possible in the agile production operation.

The capabilities extolled here are not meant to be comprehensively defining, but rather are meant to set the stage for a discussion about real machines and real production processes that do all of this. The first example we use is from the semiconductor manufacturing industry, but the principles and concepts illuminated are applicable in any industry.

The United States lost the semiconductor market to Japan in the 1970s, and hopes for regaining leadership were hampered by a noncompetitive process equipment industry—the builders of the “machine tools” for semiconductor fabrication. In this high-paced industry, production technology advances significantly every three years or so, with each new generation of processing equipment cramming significantly more transistors into the same space.

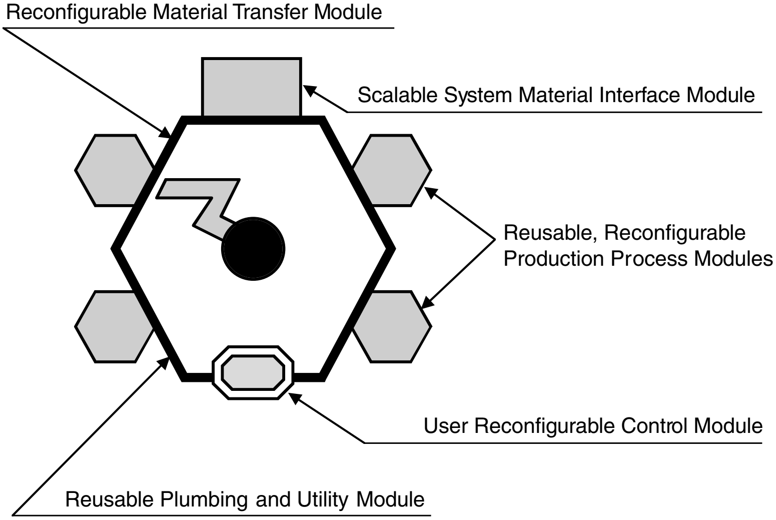
With each new generation of equipment, semiconductor manufacturers build a completely new plant, investing $250 million or more in equipment from various vendors and twice that for environmentally conditioning the building to control microcontaminants.

For equipment vendors, each new generation of process equipment presses the principles of applied physics and chemistry. Million dollar machines are developed to deposit thinner layers of atoms, etch narrower channels, imprint denser patterns, test higher complexities, and sculpt materials with new accuracy and precision. Generally each machine performs its work in a reaction chamber under high vacuum, and sports a sizable supporting cast of controls, valves, pipes, plumbing, material handling, and so forth.

New equipment development is actually new invention, frequently taking longer than the three-year prime time of its life. And because the technology used in each generation is unique, market success with one generation of equipment has little to do with the next or the previous generation. The industry's history is littered with small vendors that brought a single product-generation to market: single-purpose, short-lived, complex machines; long equipment development cycles; repeatability and reliability problems—all targeted for a high volume, highly competitive production environment serving impatient, unforgiving markets. And every new generation requires a new plant with more stringent environmental conditioning to house the new machines. The learning curve in this industry is dominated by touchy equipment that takes half its product life to reveal its operating characteristics. Forget about rework here, and get used to scrap rates way above 50 percent in the early periods of production. Heavy industry may scoff at the low scrap cost, but this means lost deliverables with a devastating loss of critical short-lived market penetration. Equipment budgets routinely factor high outage expectations into extra million-dollar machines.

Getting product out the door is so critical, and mastering the process so tough, that no one has time to question the craziness. This is the way of semiconductors.

Or rather, it was until something occurred in 1987: Applied Materials, Incorporated (AMI), a California-based company, brought a new machine architecture to market—an architecture based on reusable, reconfigurable, scalable concepts.


Reconfigurable Material Transfer Module
Scalable System Material Interface Module
Reusable, Reconfigurable Production Process Modules
User Reconfigurable Control Module
Reusable Plumbing and Utility Module

Stylized Depiction of *Precision 5000* Family from Applied Materials Inc.

FIGURE 9.1.3 Semiconductor wafer-processing cluster machines.

Depicted in Fig. 9.1.3, the AMI Precision 5000 machines decoupled the plumbing and utility infrastructure from the vacuum chamber physics and introduced a multichamber architectural concept. Instead of one dedicated processing chamber, these machines contained up to four independent processing modules serviced by a shared programmed robotic arm. Attached like outboard motors, process modules are mixed and matched for custom configured process requirements. A centralized chamber under partial vacuum houses a robotic arm for moving work-in-process wafers among the various workstations. The arm also services the transfer of wafer cassettes in and out of the machine's external material interface.

A single machine can integrate four sequential steps in semiconductor fabrication, decreasing the scrap caused by contamination during intermachine material transfer. Yield rate is everything in the competitive race down the learning curve—but this integrated modular approach pays other big dividends, too.

Applied Materials significantly shortened its equipment development time and cost by separating the utility platform from the processing technology. Development resources are focused now on process technology, reusing a utility base common across technology generations, which accounts for 60 percent of the machine. This eliminates a significant design effort for each additional process capability Applied brings to market, and shrinks the complexity and time of shakeout and debug in prototyping stages. More important, perhaps, is the increased reliability that Applied's customers enjoy with a mature and stable machine foundation.

In process sequences with disparate time differences among the steps, a configuration might double up on two of the modules to optimize the work flow through a three-step process.

A malfunction in a process module is isolated to that module alone. It can be taken off-line and repaired while the remaining modules stay in service. The architecture also facilitates rapid and affordable swap-out and replacement servicing if repair time impacts production schedules.

Semiconductor manufacturing is barraged with prototype run requests from product engineering. New products typically require new process setups and often require new process capability. When needed, redundant process modules can be dedicated to prototyping for the period of test-analyze-adjust iterations required for process parameters to be understood. And if a new capability is required, a single new "outboard motor" is delivered quicker and at less cost than a fully equipped and dedicated machine.

Cluster architecture also brings a very major savings in both time and cost for creating new fabrication facilities. The ultraclean environment needed for work in process can be reduced to controlled hallways rather than the entire building. People can attend and service the machines without elaborate decontamination procedures and special body suits.

Work in process is most vulnerable to contamination when it is brought in and out of high vacuum. The cluster machine architecture reduces these occurrences by integrating multiple process steps in one machine. Using a docking module, as depicted in Fig. 9.1.4, these machines can be directly interconnected to increase the scale of integration.

Extending these concepts and combining them with a strategy for reconfigurable facilities might push the utility services below the floor and the clean transport above the machines. Though this "ultimate" configuration shown in Fig. 9.1.5 does not yet exist in a production environment, the possibility is obvious.

In 1989 the Modular Equipment Standards Committee of SEMI (Semiconductor Equipment and Materials International) started work on standards for mechanical, utility, and communications interfaces. What started as a proprietary idea at Applied Materials is moving toward an industry open architecture, promising compatible modular process units from a variety of vendors.

Applied Materials revolutionized the semiconductor industry. Their cluster machines propelled them into global leadership as the largest semiconductor equipment supplier in the world. Leadership is defined by followers, and today, every major equipment supplier in the world has a cluster tool strategy.

Cluster strategy illustrates the 10 RRS design principles introduced in the last section in action, with an agile machine architecture that enables an agile production environment. Next we will look at an equally agile metal-cutting production operation, but with machine tools that are not themselves agile.

AGILE CELLS AND AGILE PRODUCTION

Manufacturing cells in general and flexible machining cells in particular are not especially new concepts, though their use and deployment is still in an early stage. Machining centers are

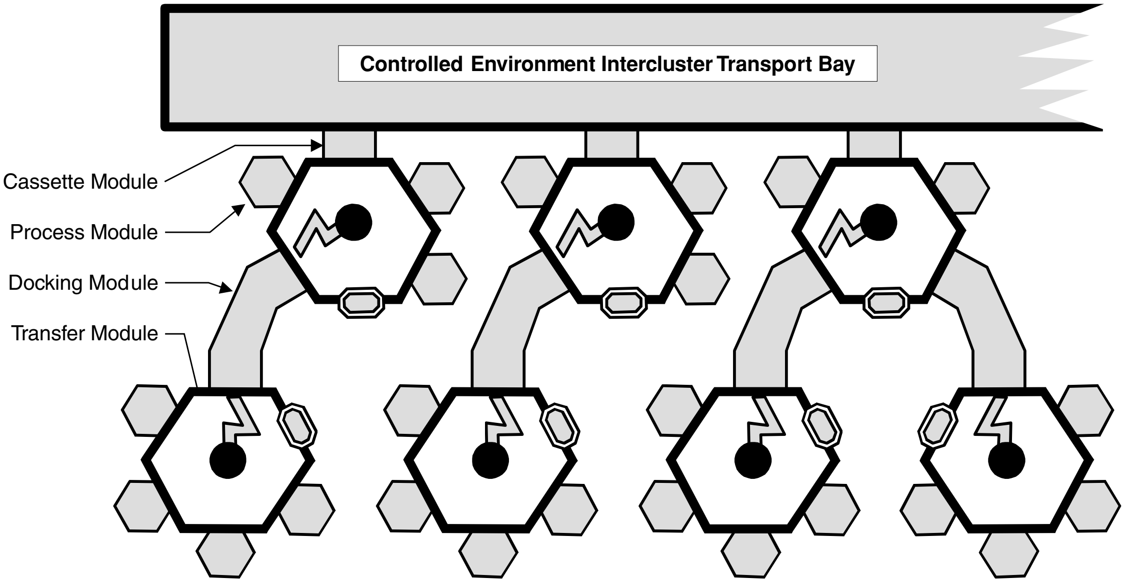

Controlled Environment Intercluster Transport Bay
Cassette Module
Process Module
Docking Module
Transfer Module

FIGURE 9.1.4 Scalable machine clusters.

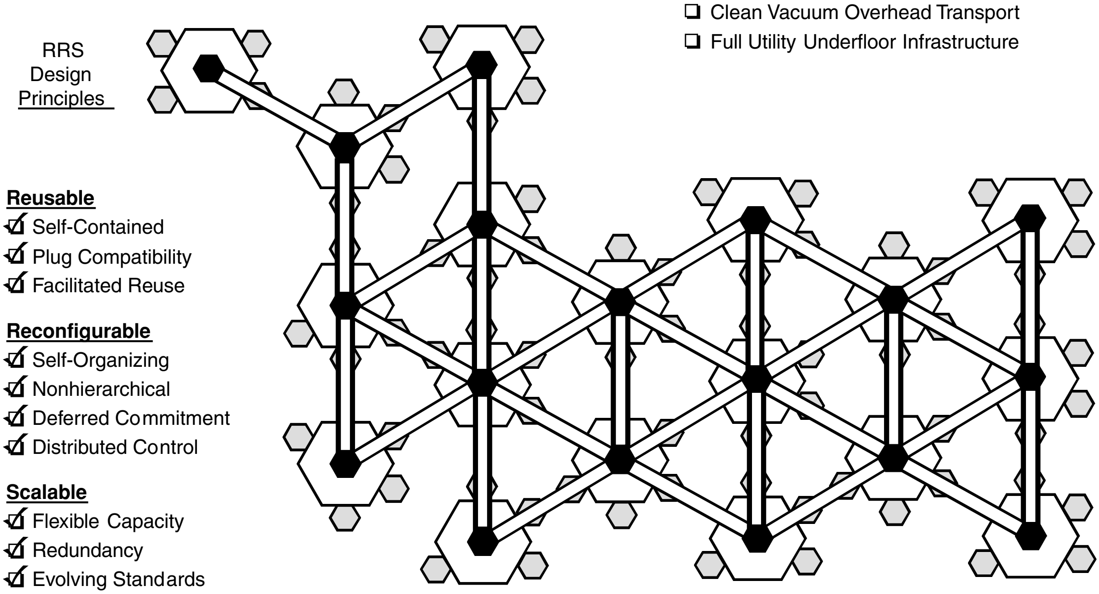

☐ Clean Vacuum Overhead Transport
☐ Full Utility Underfloor Infrastructure
RRS Design Principles
Reusable
☑ Self-Contained
☑ Plug Compatibility
☑ Facilitated Reuse
Reconfigurable
☑ Self-Organizing
☑ Nonhierarchical
☑ Deferred Commitment
☑ Distributed Control
Scalable
☑ Flexible Capacity
☑ Redundancy
☑ Evolving Standards

FIGURE 9.1.5 Agile machines in a reconfigurable plant framework.

not inexpensive machine tools, and the economics of building cells from multiples of these machines is still beyond the vision and justification procedures for many manufacturers. It is typical to expect benefits from these flexible machining cells in production operations with high part variety and low volume runs. When justification and benefit values are based on flexible configurations and objectives this is understandable.

Currently, however, innovators are finding important values in quick market response: rapid new product introduction, accommodation to unpredictable demand, fast prototype turnaround, non-premium-priced preproduction runs, efficient ECO incorporation, longer equipment applicability, and the latitude to accept (or insource) atypical production contracts to improve facility utilization.

These new agile system values now challenge applications where transfer lines and dedicated machinery have traditionally reigned—and their applicability is based on concepts that push beyond the traditional flexible values. After examining these values Kelsey-Hayes decided to build two entirely cellular plants for the production of anti-lock braking systems (ABS) and other braking systems. "We want to achieve a strategic advantage on product cost and delivery," was the vision voiced by Richard Allen, president of their Foundation Brake Operations [5].

We are not talking mass customization here, with custom configured products. We are talking about fundamental change in the value structure of the high-volume-car/high-volume-brake markets. Technological advances in ABS have cut each succeeding product generation's lifetime in half.

The trend to higher automotive-system integration and advanced technology promises even more change. Car companies want leadership in functionality and feature, and faster times to market—and cannot afford to feature obsolete systems when competitors innovate. Kelsey-Hayes sees opportunity in this faster paced, less predictable market.

To put the problem in perspective and provide a basis for evaluating the depicted solutions, we will look at some change proficiency issues first.

Product life cycle for ABS has dropped from 10 years to 3 years over three generations of product, and is expected to go lower yet—so taking 4 to 6 months to retool a dedicated transfer line is a significant part of the production life, and is not good. As automakers mine new niche markets and increase total systems integration in standard models, the frequency of ABS model-change increases. Within this shortened life of any model is the increasing frequency of modifications to add feature advantages and necessities. Of course, all these modifications and new models do not spring to life from pure paper—they each need prototypes and small preproduction runs.

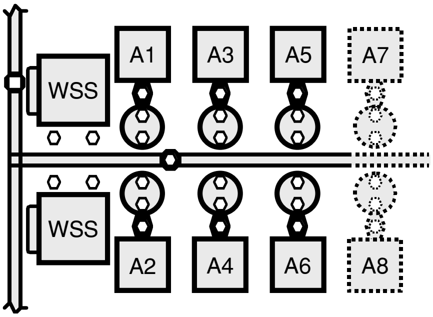
Automakers, like most everyone else, have never been able to forecast demand accurately, and it is only getting worse. Coupled with new just-in-time (JIT) requirements and reduced finished goods auto inventories, automakers need to throttle production in concert with demand on a week-by-week basis. Suppliers must either be proficient at capacity variation or face increased costs with their own finished goods inventories and obsolete scrap.

The ABS market is not alone in this application of technology and continual improvement; some machine tool advances are following the same method. Previously we examined an agile semiconductor–production machine architecture and how those machines might (and do) support an agile production operation. We continue the illumination of design principles that give us agility by looking at an agile cell architecture and how it supports an agile production operation. Both the agile cell (Fig. 9.1.6) and the agile production environment (Fig. 9.1.7) make use of capabilities and configurations possible with the LeBlond Makino A55 machining centers, and are substantially similar to actual installations. Perhaps other vendors can provide a similar capability; our purpose in using the LeBlond example is to show that these concepts are real and not imagined.

The depiction of the agile machining cell in Fig. 9.1.6 includes a synopsis of some of the change proficiencies obtained by the configuration. Flexible machining cells have been implemented in many places, but the agile configuration here brings additional values. The configuration and the specific modules were chosen to increase the responsiveness to identified

Change proficiency

Install and Set Up New Cell in 4–8 Weeks.
Reconfigure Cell for Entirely New Part in 1–4 Weeks.
Duplicate Cell Functionality in 1–2 Days.
Add/Calibrate New Machine in 1–2 Days While Cell Operates.
Remove or Service Machine without Cell Disruption.
JIT Part Program Download.
Insert Prototypes Seamlessly.



Concept Based on LeBlond Makino A55 Cells at Kelsey-Hayes

Observed RRS design principles

Reusable

Self-contained—machines, work-setting stations, pallet changers, fixtures.
Plug compatibility—common human, mechanical, electrical, and coolant framework.
Facilitated reuse—machines do not require pits or special foundations, and are relatively light and easy to move.

Reconfigurable

Self-organizing—cell control software dynamically changes work routing to accommodate module status changes and new or removed modules on the fly.
Nonhierarchical—complete autonomous part machining, nonsequential.
Deferred commitment—machines and material transfers are scheduled by cell control software in real time according to current cell status, part programs downloaded to accommodate individual work requirements when needed.
Distributed control—part programs downloaded to machines, machine life history kept in machine controller, machines ask for appropriate work when ready.

Scalable

Flexible capacity—cell can accommodate any number of machines and up to four work setting stations.
Redundancy—all modules are standard and interchangeable with like modules, cells have multiple instances of each module in operation, machines capable of duplicate work functionality.
Evolving standards—utility services and vehicle tracks can be extended without restrictions imposed by the cell or its modules.

FIGURE 9.1.6 Agile machining cell.

types of change. The LeBlond Makino A55 horizontal machining centers do not require pits or special foundations, so they are (relatively speaking) easy to move. A cell can increase or decrease its machining capacity in the space of a day and never miss a lick in the process. This is facilitated by a plant infrastructure of common utility, coolant, mechanical, and human interfaces that provide a framework for reconfiguring modules easily. These and other reusable/reconfigurable/scalable system design principles are detailed in the depiction.

It is accepted knowledge that replacement or massive retooling of a rigid production module is more expensive than transformation of a flexible production module. Now we see where agile system configurations can further change the economics to overcome an initial investment that has been higher. “Has been” should be stressed. The price/performance ratios of modular production units are becoming better as increased sales increases their production quantities.

Do not let the examples introduced so far lead you to a wrong conclusion. Agile production requires neither agile nor flexible machines—for the agility is a function of how the modules of production are permitted to interact. An agile system must be readily reconfigurable,

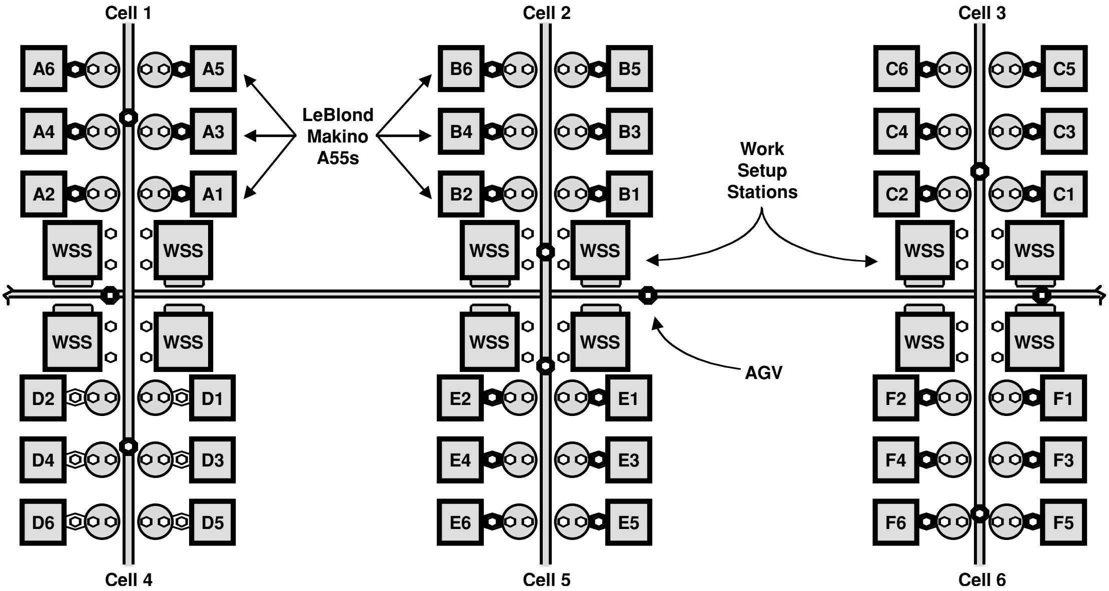


FIGURE 9.1.7 Agile machining cells in reconfigurable framework.

and may gain this characteristic by simply having a large variety of compatible but inconsistently or infrequently utilized production units.

The toy industry is an example where this is a common approach. Not knowing from year to year what kinds of toys kids will want until a few months before volume deliveries are required, toy manufacturers are either highly vertically integrated (with poor resource utilization) or broadly leveraged on outsourced manufacturing potential. Agility is a relative issue—and the toy industry has few alternatives to either agile outsourcing or just-in-case vertical integration. As virtual production concepts mature to support agile outsourcing, this approach might become more proficient then the just-in-case captive capability alternative—unless of course those practitioners become proficient at insourcing other companies' needs to cover the costs of their insurance base.

From the enterprise viewpoint an agile production capability can be built from a reconfigurable network of outsources.

AGILE ENTERPRISE AND AGILE PRODUCTION

The agile enterprise is adaptable enough to transform itself proficiently into whatever current trends require. At least, with the unpredictable and increased pace of change driving companies out of business today, that is the salvation hoped for by corporate management. They understand that business is not just about making money, it is also about staying in business. We used to think that making money was all it took to stay in business. Now we know that you can make money right up to the day you become irrelevant—then you are probably the last to know while you are ignored to death.

A corporation stays alive because customers continue to pay more for goods than the "real" cost of production. This excess payment is required to cover the cost of production inefficiencies (nothing is perfect) and the cost of preparing for new goods to replace ones that (eventually) lose favor. With increased global competition, it is getting harder to fund these production inefficiencies; someone is always finding a better way to produce the same thing. With faster technological obsolescence, it is getting harder to fund the preparation for new goods; reduced product life generates both less investment cash and a higher risk of investing in the wrong thing.

The profit-making predictability of any company that wants to outlive its currently successful product family becomes more important and more difficult than ever. The marketplace grows less tolerant of mistakes and inefficiencies, and deep pockets are getting shallower. Borrowing from one successful area of a business to cover problems in another increases the threat to all.

Resources that were correct for customer satisfaction only yesterday may no longer be relevant today. With the increased risk to the entire business comes sharpened recognition that every internal resource must either be making profits today or insuring profits tomorrow.

The boardroom knows this, and business reengineering is proceeding accordingly. Most companies “leaned” out in the mid-1990s. Downsizing was the dominant strategy employed by companies seeking leaner operating modes, and outsourcing was the strategy for increasing responsiveness.

Nobody likes the downsizing process, but cost and skill mismatches threaten the viability of the entire corporation. When business picks up or new products enjoy high demand, these downsized corporations are not upsizing as they once would—instead they are seeking alternative ways to gain the necessary skills and capability without the inertia of captive resources. Consulting and professional-temp organizations are growing to fill the gap for managerial and professional help, contract manufacturing is providing new options for fluctuating production capacity, and outsourcing in general is broadening the capabilities and capacities available to a company on quick notice.

Successfully living with fickle markets and unpredictable technological change requires a higher frequency and freedom of resource reconfiguration than in the past. Looking at it from the corporate view, gaining new productive capacity as well as new productive capability through outsourcing has several potential advantages: short-term requirements are not burdened with long-term costs, capital investment and its associated risk are both eliminated, the learning curve to develop new production competency is eliminated, and unit costs may well be lower.

Contract manufacturers and outsource firms are thriving. At least the good ones are. They are focusing on areas where they have a high degree of competency, innovating in these areas to maintain leadership, organizing common-process production facilities applicable to a variety of manufacturing customers, and loosely coupling the elements of production so that they can be reconfigured to meet demand fluctuations among their customers. Many reach advantageous scale economies by aggregating similar needs of multiple customers, and in any event spread their risk over a broader base of market servers. The Kelsey-Hayes company is a prime example of these points.

On the internal production downside, operations in large corporations often carry baggage filled by many captive years, generally lack local authority to invest in the future, and typically subsidize less effective sister operations.

At the corporate level, with or without a conscious corporate strategy, most companies are moving toward agility—some faster than others. They have no choice. Too much inertia impedes the ability to capitalize on market opportunities and hampers the ability to bring innovation to fruition. The continued survival of any corporation demands a more agile operating capability, and most corporate strategies are following a path in this direction.

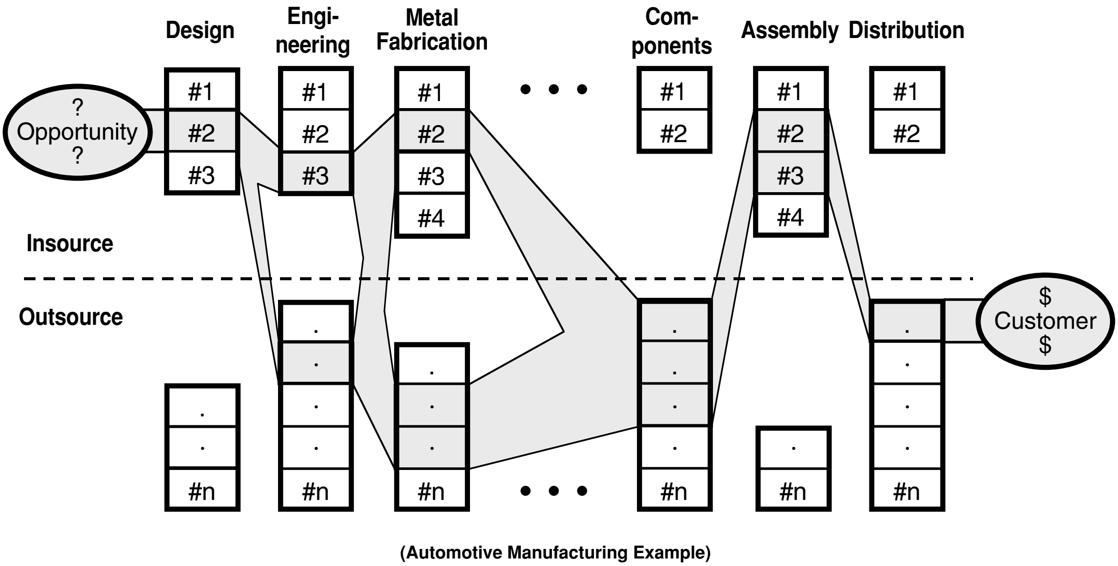
There are, however, many paths. We have previously looked at the paths that build agile production from agile machines and agile cells. Now we look at a path that builds agile enterprise from agile production, and we look from the corporate view where there are alternatives—if there is a will.

From the enterprise point of view, agile production is achieved when the makeup and relationships of the enterprise’s production resources are easily adapted to the precise needs of the moment, and a fleeting moment it is. The internal strategy breaks the company into independent functional resource units that look like one big job shop (see Fig. 9.1.8) where units bid on work based on their performance capabilities. Good performance is rewarded with lots of jobs, bad performance is starved to death, and the system is self-organizing. Some units learn and improve, others get traded out, shut down, or simply ignored to death. Subsidies are replaced with local profit responsibility and investment authority.

Nucor Steel decentralized decision making so much in the mid-1990s that plant managers found their own raw materials, found their own customers, and set their own production quotas. Sure, there are efficiencies to be gained with centralized purchasing—and a crushing price to pay in overall corporate health. These are not lonely ideas: an irrefutable success base abounds. Nor are they simply another swing of the centralize-decentralize cycle seen in older corporations with history.

The external strategy recognizes that production resources do not necessarily have to be owned and captive; they only have to perform effectively when needed. Outsourcing and contract manufacturing enters the corporate mix of possibilities here (see Fig. 9.1.9). When a good system is set up, these outside alternatives are not used as threats to distort internal costing, but rather as a self-organizing influence that brings best-in-class to the table. If management values the retention of captive resources it builds a system that levels the real difference over a reasonable time. Invariably this leads back to local responsibility and local authority. Internal units that must compete with best-in-class external alternatives are allowed to compete on an even basis. And by the same token, they are able to find other customers that will help maintain a balanced production rate, justify new capability investment, and inspire innovative leadership.

From the corporate point of view these liberated internal resources are incomparably stronger assets than they were as exclusive captives. Stronger as profit generators for the corporate coffers and stronger as reliable best-in-class suppliers. A good system might institute a most-favored-nation relationship with some group profit sharing plans as the tie that binds. Large partner-based organizations like Andersen Consulting offer interesting models here.



Resources Bid on Opportunity Fulfillment

FIGURE 9.1.8 Enterprise job shop.

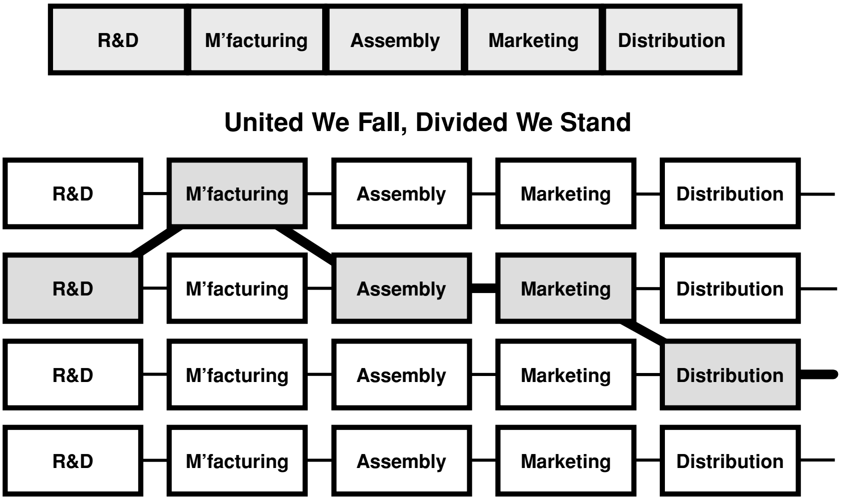


FIGURE 9.1.9 Loosely coupling the enterprise.

So what is a plant manager to do if stuck in a corporate environment where the agility decisions are being made at the higher levels. A plant manager, with hands tied, is likely to favor the outsourcing alternatives. Think about it—we all know it is cheaper to get it ready-made elsewhere than it is to re-tailor the resources we have; we must—observation says that this is human nature.

A plant manager could take a job with one of these outsourcing firms that has all the advantages. Some have. Some keep marching with their heads down figuring they will retire before the inevitable happens. A few might see the inherent advantage that an internal resource has with the corporation if it is an irresistible member of the family.

People get downsized, plants get outsourced. But nobody outsources a plant that can respond to the changing corporate needs, just as nobody downsizes the employee that keeps one step ahead of the employer's needs.

Viable business entities are those that can keep up with the mercurial markets that are only going to get more slippery. The agile enterprise is an imperative, and it will happen with or without captive agile plants. But those that have agile plants will have a more robust and broader scope foundation.

You can build an agile system out of rigid in-agile modules by considering those modules expendable. Thus, you can have an agile enterprise composed at any one time of in-agile production facilities, wholly unowned and virtual, and replaceable at whim and will. But when the enterprise includes captured and enduring business units, the agility of each captured unit becomes important to the agility of the total enterprise. If they are rigid rather than agile, they become defining anchors. They must either be agile enough to transform as needed when needed, or they too must be replaced. And replacing an owned unit, unlike an outsourced unit, is a change transformation that exacts a toll.

When RRS design principles are employed, replacement of a rigid module is more expensive than transformation of an agile module. Thus, it costs more to fire and hire than it does to retrain (an agile person). Of course, if you are dealing with a contract employee, one you do not own and can consider expendable, than you have our other model of an agile system.

Plant management that waits for the corporate light to go on may see it shine in a different room. As a newscaster in San Francisco used to say: "If you don't like the news, go out and make some of your own." Agile production is not dependent on machinery and capital investments—as the corporate alternatives clearly show. Good application of RRS principles with people, organization, and practices can make a decisive difference in the response ability of any plant before the corporate strategists consider the options.

DESIGN PRINCIPLES FOR AGILE PRODUCTION

We have been exploring the nature of agility in production systems and occasionally the enterprise systems that encompass them, making the argument more than once that agility is a characteristic that emerges from design. Behind each of these systems are business engineers responsible for the system's design—consciously or unconsciously as the case may be.

Good engineering is applied science. Some would argue about management as science, and others believe a manufacturing science remains elusive. Nevertheless, the design of manufacturing enterprise systems, from production process to business procedure, can result in a more or less adaptable system to the extent that certain design principles are employed. The expression of RRS design principles explored in three production systems (see Fig. 9.1.10) is assembled in Fig. 9.1.11 in tabular form, showing various applications.

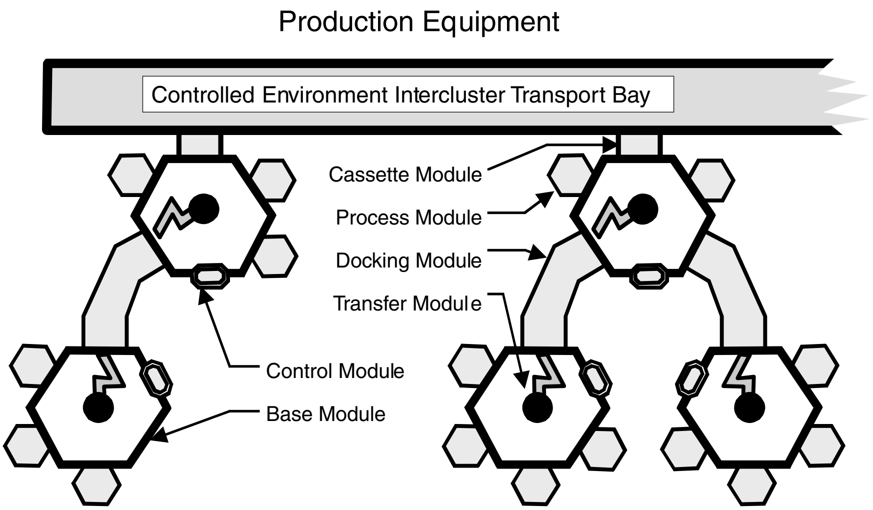
Science is born from gathering data, analyzing this data for patterns, making hypotheses on principles, and iterating toward validation. The 10 principles employed here have been discovered, refined, and validated in numerous analytical exercises [6]. Though this process is not complete at this writing, we have found useful repeatable patterns that appear to govern adaptability. Methods for conducting change proficiency analysis in your production environment, and building customized change proficiency maturity profiles or your competitive agility can be found in *Response Ability—Understanding the Agile Enterprise* [7].

Few would disagree that information automation systems are critical enablers for modern production, but what will the information automation system do to support an agile operating environment? Perhaps more important, what will make the system itself agile so that it can continue to support an agile operating environment rather than guarantee its obsolescence? Are there fundamental characteristics that provide agility that we can look for in selecting information automation systems?

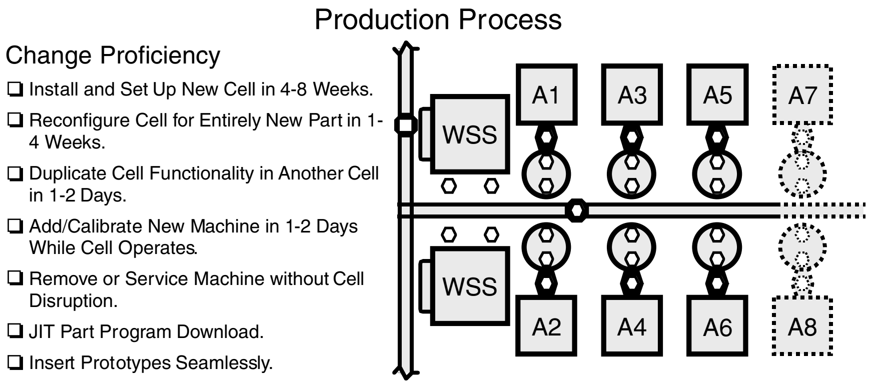
Adaptability (agility) actually became a reasoned focus with the advent of object-oriented software interests in the early 1980s. The progress of software technology and deployment of large integrated software systems has provided an interesting laboratory for the study of complex interacting systems in all parts of enterprise. The integrated software system, whether it is in the accounting area, providing management decision support, or spread over countless factory computers and programmable logic controllers, is understood to be the creation of a team of programmers and system integrators. We recognize that these people also have the responsibility for ongoing maintenance and upgrade during the life of the system. In short, the integrated software system is the product of intentional design, constant improvement, and eventual replacement with the cycle repeating.

As engineering efforts, the design and implementation of these integrated software systems proceeds according to an architecture, whether planned or de facto. By the early 1980s the size and complexity of these systems grew to a point where traditional techniques were recognized as ineffective. This awareness came from experience: from waiting in line for years to get necessary changes to the corporate accounting system, from living with the bugs in the production control system rather than risk the uncertainty of a software change, and from watching budgets, schedules, and design specifications have little or no impact on the actual system integration effort.

The problem stems from dynamics. Traditional techniques approach software design and implementation as if a system will remain static and have a long and stable life. New techniques, based on object-oriented architectures, recognize that systems must constantly change, that improvements and repairs must be made without risk, that portions of the system must take advantage of new subsystems when their advantages become compelling, and that interactions among subsystems must be partitioned to eliminate side effects.


Production Equipment
Controlled Environment Intercluster Transport Bay
Cassette Module
Process Module
Docking Module
Transfer Module
Control Module
Base Module

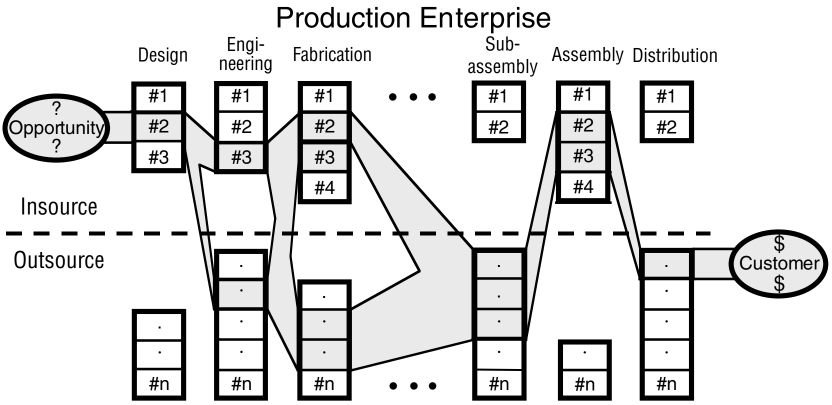
Stylized Depiction of *Precision 5000* Family, from Applied Materials, Inc.


Production Process
WSS
A1
A3
A5
A7
WSS
A2
A4
A6
A8

Change Proficiency

- ☐ Install and Set Up New Cell in 4-8 Weeks.
- ☐ Reconfigure Cell for Entirely New Part in 1-4 Weeks.
- ☐ Duplicate Cell Functionality in Another Cell in 1-2 Days.
- ☐ Add/Calibrate New Machine in 1-2 Days While Cell Operates.
- ☐ Remove or Service Machine without Cell Disruption.
- ☐ JIT Part Program Download.
- ☐ Insert Prototypes Seamlessly.

Concept Based on LeBlond Makino A55 Cells at Kelsey-Hayes


Production Enterprise
Design
Engi-neering
Fabrication
Sub-assembly
Assembly
Distribution
? Opportunity ?
#1
#2
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#4
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Insource
Outsource
$ Customer $

Resources Bid on Opportunity Fulfillment

FIGURE 9.1.10 Agile production configurations.

RRS	Design principles	Production equipment (cluster machines)	Production process (agile machining cell)	Production enterprise (enterprise job shop)
Reusable	*Self-contained units:* System of separable self-sufficient units not intimately integrated. Internal workings unimportant externally.	Wafer-transfer module, various process modules, docking module, cassette transfer module, utility-base module.	Machines, work-setting stations, pallet changers, fixtures, rail-guided vehicles.	Design, engineering, fabrication, subassembly, assembly, and distribution resource modules.
	Plug compatibility: System units share common interaction and interface standards, and are easily inserted or removed.	Common human, mechanical, electrical, vacuum, and control system interfaces.	Common human, mechanical, electrical, and coolant system interfaces. Common intermodule mechanical interfaces.	Common information system and procedures among captured corporate resources, common interface in outsourcing contracts.
	Facilitated reuse: Unit inventory management, modification tools, and designated maintenance responsibilities.	Machine manufacturer extends/replicates module family for new capabilities. Fast module-swap maintenance is facilitated.	Machines do not require pits or special foundations, and are relatively light and easy to move.	Corporate outsourcing department maintains prequalified pool of potential outsources.
Reconfigurable	*Nonhierarchical interaction:* Non-hierarchical direct negotiation, communication, and interaction among system units.	Processing modules decide how to meet part production objectives with closed-loop controls.	Complete autonomous part machining, direct machine-repository download negotiation.	Business unit resources free to bid on internal jobs and external jobs.
	Deferred commitment: Relationships are transient when possible; fixed binding is postponed until immediately necessary.	Machine custom configured with processing modules at customer installation time.	Machines and material scheduled in real time, downloaded part programs serve individual work requirements.	Individual business unit assigned to opportunity fulfillment at last possible moment.
	Distributed control and information: Units respond to objectives; decisions made at point of knowledge; data retained locally but accessible globally.	Intelligent process modules keep personal usage histories and evolving process characterization curves.	Part programs downloaded to machines, machine history kept in machine controller, machines ask for work when ready.	Enterprise integration information system queries databases local to the business unit.
	Self-organizing relationships: Dynamic unit alliances and scheduling; open bidding; and other self-adapting behaviors.	Real-time control system makes use of processing units available at any given time, scheduling and rerouting as needed.	Cell-control software dynamically changes work routing for status changes and new or removed machines on the fly.	Bid-based production-flow alliances.
Scalable	*Flexible capacity:* Unrestricted unit populations that allow large increases and decreases in total unit population.	Machines can be interconnected into larger constant-vacuum macroclusters.	Cell can accommodate any number of machines and up to four work-setting stations.	Outsourced resources can be easily added or deleted to increase the population of production modules with no size restrictions.
	Unit redundancy: Duplicate unit types or capabilities to provide capacity fluctuation options and fault tolerance.	Machine utility bases are all identical, duplicate processing chambers can be mounted on same base or different bases.	Cells have multiples of each module, all cells made from same types of modules, machines have full work functionality.	Multiple duplicate production resources and second outsources.
	Evolving standards: Evolving, open system framework capable of accommodating legacy, common, and completely new units.	Base framework becoming standard across vendors, and has accommodated processing technology across generations.	Utility services and vehicle tracks can be extended without restrictions imposed by a cell or its modules.	Enterprise integration information system is open architecture, client/server based.

FIGURE 9.1.11 RRS design principles employed in agile production configurations.

These new approaches have been maturing for almost two decades now, and have emerged most visibly into everyday employment under the name client/server architecture. Although there are significant differences between systems concepts called client/server and those called object-oriented, encapsulated modularity and independent functionality are important and shared key concepts. More to the point, information automation practitioners are now focusing a good deal of thought on the architectures of systems that accommodate change, providing a rich laboratory and experience base from which fundamental agile-system principles are beginning to emerge.

The 10 RRS design principles introduced earlier and tabulated in Fig. 9.1.11 grew from object-oriented concepts and have since been augmented with understandings from production and enterprise systems that exhibit high degrees of adaptability.

The choice of terminology for these 10 principles is important. Would-be users far removed from systems engineering or computer technology may find some words used to describe these principles too abstract at first. For instance, the first principle was initially called *encapsulated modules.* A human resources director suggested the more generic *self-contained units,* which he could readily translate into empowered work team.

The RRS design principles identified here are presented as a useful working set that will undergo evolution and refinement with application. Their value is in their universal applicability across any system that would be adaptable. Instead of simply lurching to the next competitive state, RRS design principles facilitate continuous evolution.

Next we will look at two real-life case studies that were captured and cataloged during analytical workshops conducted in mid-1997 [6]. The purpose of these workshops was to analyze production activities that exhibited high degrees of adaptability—and to look for evidence of the 10 RRS principles in action.

CASE STUDY: ASSEMBLY LINES—BUILT JUST IN TIME

You work in a General Motors (GM) stamping plant outside of Pittsburgh that specializes in after-model-year body parts. Your principal customer is GM's Service Parts Organization. They might order 1973 Chevelle hoods, quantity 50; 1984 Chevy Impala right fenders, quantity 100; or 1989 Cutlass Supreme right front doors, quantity 300. Your plant stamps the sheet metal and then assembles a deliverable product. Small lots, high variety.

Every new part that the plant takes on came from a production process at a GM original equipment manufacturing (OEM) plant that occupied some hundreds of square meters (thousands of square feet) on the average, and the part was made with specialized equipment optimized for high volume runs and custom-built for that part's geometry. To stamp a new deck lid (trunk door) part you bring in a new die set—maybe six or seven dies, each the size of a full grown automobile, but weighing considerably more. And you bring in assembly equipment from an OEM line that might consist of a hemmer to fold the edges of the stamped metal, perhaps a prehemmer for a two-stage process, dedicated welding apparatus for joining the inner lid to the outer lid, adhesive equipment for applying mastic at part-specific locations, piercer units for part-specific holes, and automated custom material handling equipment for moving work between process workstations.

You received a call a few weeks ago that said your plant will start making the Celebrity deck lids, and production has to start in 21 days. Not too bad—sometimes you only have 4 days. For new business like this your job is to get the necessary assembly equipment from the OEM plant, reconfigure the equipment and process to fit your plant, and have people ready to produce quality parts in the next 3 weeks. Others are responsible for the die sets and stamping end of the production process.

In the last 12 months this happened 300 times. In the last 5 years you have recycled some 75,000 m^2 (800,000 ft^2) of floor space in OEM plants for new model production. At this point you have assembly equipment and process for some 1000 different parts—but no extra floor space.

And no extra floor space materialized in your plant either. Good thing you have not needed it; the core competency here is rapid new-part starts, and small-lot, high-variety production—in a business that is traditionally based on high-volume economics—and you have learned to do it without the usual capital budget. After eight years some unique techniques—and a unique culture—have evolved.

You do not do this by yourself: You are a team leader that may use almost anyone from anywhere in the plant. At this point almost everyone is qualified to help bring in new work—surviving under these conditions has developed a self-confident attitude in almost everyone, and a shared understanding of how to get the job done.

Eight years ago the plant went to a single job classification in production, cross-training everyone on everything—a press operator might change dies one day, the next day work in the assembly area building hoods in the morning and fenders in the afternoon, and the following day travel to another plant to review a piece of equipment or a part to determine how to bring it back.

For this new business one of the guys on the last recon team wants to lead this one. Last time he experimented with his video camera. Now he thinks he is ready to do a perfect taping job. He got the idea himself on that last job while trying to bring several jobs at once back from another GM facility. This environment encourages self-initiative.

In addition to taping the operational assembly process he added close-ups of key equipment pieces. In the debrief review everyone saw the same thing at the same time—there was almost no debate over what to bring back and what to ignore—and you got a jump on the equipment modifications by seeing what was needed in advance. Some time ago the value of having a good cross section represented in these reviews became evident: nobody is surprised, everyone shares their knowledge, and when the equipment arrives the modification team is prepared.

Two key factors are evident at this stage: (1) knowing what to bring back, and (2) knowing what modifications to make.

This new deck lid would be handled by bringing back the hemmer only, ignoring the mastic application machine, two welding robots, the welding fixtures, two press piercers, the shuttles, the press welders, and three automated material handling fixtures—basically bringing back a feet-print of 19 m^2 (200 ft^2) from a process that covered 230 m^2 (2500 ft^2). The rest will go to salvage disposition while the hemmer goes to "hemmer heaven"—that place in your plant where some 200 different hemmers hang out until needed.

That you only need the hemmer is where a key part of the plant's unique core competency comes into play. Rather than build a growing variety of product on some sort of omnipotent universal assembly line, a line that grows to accommodate next year's unpredictable new business as well as the last 10 to 20 years of legacy parts, this plant builds a custom assembly line for each product—and builds that assembly line just before it runs a batch of, say, 300 hoods. When the hoods are done, you tear down the assembly line and build another one for fenders, perhaps, on the same floor space—and then run 500 or so fenders. Tear that down and build the next, and so forth. The same people who built the hoods build the fenders, and the deck lids, and the doors, and the . . . ; and tomorrow some of them will be running a press, changing press dies, or running off to evaluate the next incoming equipment opportunity.

Necessity is the mother of invention, and the driving force here is the unrelenting requirement to increase product variety—without increasing costs or making capital investments. But fundamentally, for assembly, the scarcest resource is floor space.

Yes—a newly built customized assembly line for each and every small-batch run, every time, just in time.

The plant has six assembly areas, and can build any part in any of those areas. Usually you like to do the deck lids in the A area, though, because it has the most flexibility for welding.

While you were waiting for that new hemmer to arrive you got the process system configuration designed. Usually the same two people do this working as a team. Once they figure out which assembly modules are best and how they should be spaced, they put together a configuration sheet (see Fig. 9.1.12) for the assembly system by cutting and pasting standard icons for each module, and running it through the copy machine. The development of these configuration sheets is another example of simple reconfigurable system generation.

AGILE PRODUCTION: DESIGN PRINCIPLES FOR HIGHLY ADAPTABLE SYSTEMS

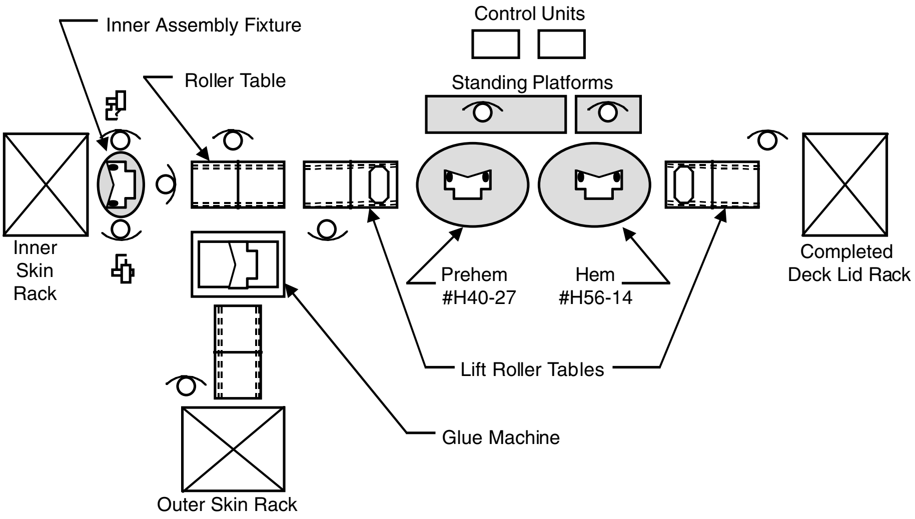


FIGURE 9.1.12 Configuration sheet: P14 deck lid assembly line.

It was not always this easy, but you have learned a lot over the years. You build these assembly systems according to these one-page configuration diagrams kept in a three-ring binder—in real time from reusable modules. Modules are easily moved into place and they share common interface standards and quick disconnects. On the average it takes about 15 min to break down the last assembly system and configure the next one.

First rule: Nothing is attached to the floor permanently. If it cannot be lifted and carried easily by anybody, it will have wheels, or as a last resort, forklift notches.

A typical deck lid assembly sequence might hem the outer skin, mastic some cushioning material to the inner skin, then weld a brace into place, and finally weld the inner skin to the outer skin in 30 places. In the process, the material has to be turned over once and some gauging is done. The assembly system configuration might call for two 1 m-long (3 ft) roller tables in the front to receive the inner and outer pieces—think of these as hospital gurneys, on wheels, with rollers on top so the "patient" can be rolled across the table to the next station when the designated operation is completed. Next in line for the outer skin is the hemmer. It is on wheels too, and it is quick-connected to a standard controller off on the side, out of the way. Yes, the controller is on wheels, too. The outer skin is lifted into the hemmer with the aid of an overhead TDA Buddy, which is one advantage of doing lids in area A: two TDA Buddies hang from the ceiling grid. When deck lids are assembled in another area a variant of the roller table is used that includes lifting aids. After hemming, inner and outer skins move to roller tables under the welding guns. The configuration sheet shows how many guns are active, where to position them, and which tip variant to install. All told there might be 12 simple icons on the sheet positioned in a suggested geometry.

A hemmer is a very specialized piece of machinery. When it arrives at this plant it loses most of its specialness, and becomes plug compatible with all the other modules in the just-in-time assembly family. More important, the hemmer's integrated controls are removed and quick-connect ports installed to interface with the one standard electronic/hydraulic controller used for all hemmers. It is modified if necessary to work with one of the six standard control programs. Maybe a seventh will be added some day, but six have covered all needs so far. Finally, the setup sequence for the hemmer is typed up and attached to its side—better there than in a file drawer.

Hemmers are pooled in hemmer heaven awaiting their time in the assembly area—each one being individually part specific. Other pools hold variants of standardized modules that have use in multiple assembly systems: 12 different types of roller tables, 2 types of quick-connect weld guns, 3 types of weld tips, 1 standard controller type, 6 standard downloadable controller programs, and other reusable standardized items.

Whatever the configuration sheet shows is quickly carried, rolled, or forked into place, quick-connected or downloaded if required, and ready for action. The assembly area has an overhead utility framework that enables the adaptability below; providing tracked weld-gun hookups, quick-connect power, and air, light, and water. The operating atmosphere is not unlike the hospital operating room—except patient throughput is a lot faster—fast enough to satisfy service parts economics.

It is common for production team members to make real-time changes to the configuration when they find a better way. Better is better, and everyone knows what that means.

Second rule: People rule. These assembly systems take advantage of the fact that people think better and adjust better than automated positioning devices, cast-in-stone configuration sheets, and ivory-tower industrial engineers. People bring flexibility when they are enabled and supported, but not constrained, by mechanical and electronic aids.

There is a lot more in this vein that is equally thought provoking. Next we will look at a completely different lesson in innovative adaptability from this same plant—and see where common concepts emerge.

CASE STUDY: FIXTURES BUILT WHILE YOU WAIT

We are still in Pittsburgh, at the GM service-parts metal-fabrication plant. We have already looked at their just-in-time assembly concept; now we will examine a check-fixturing technique for auto-body-part contour verification: two very different aspects of production that exhibit uncommonly high degrees of adaptability.

Is there a common set of design principles responsible for this adaptability? A warning: We are going to look pretty closely at the architecture of this check-fixturing concept—and there will be a test later.

Picture a room about 9 by 12 m (30 by 40 ft). In the middle, on the floor, is a 3 by 7 m (9 by 23 ft) cast-iron slab 30 cm (1 ft) thick. You cannot see much of this slab because it is mostly covered with four smaller plates of aluminum, each approximately 1 by 2 m (3 by 7 ft) and 10 cm (4 in) high. These plates are punctured by a pattern of holes on a 55-mm grid, looking like an industrial strength Lego™ sheet just waiting for some imaginative construction.

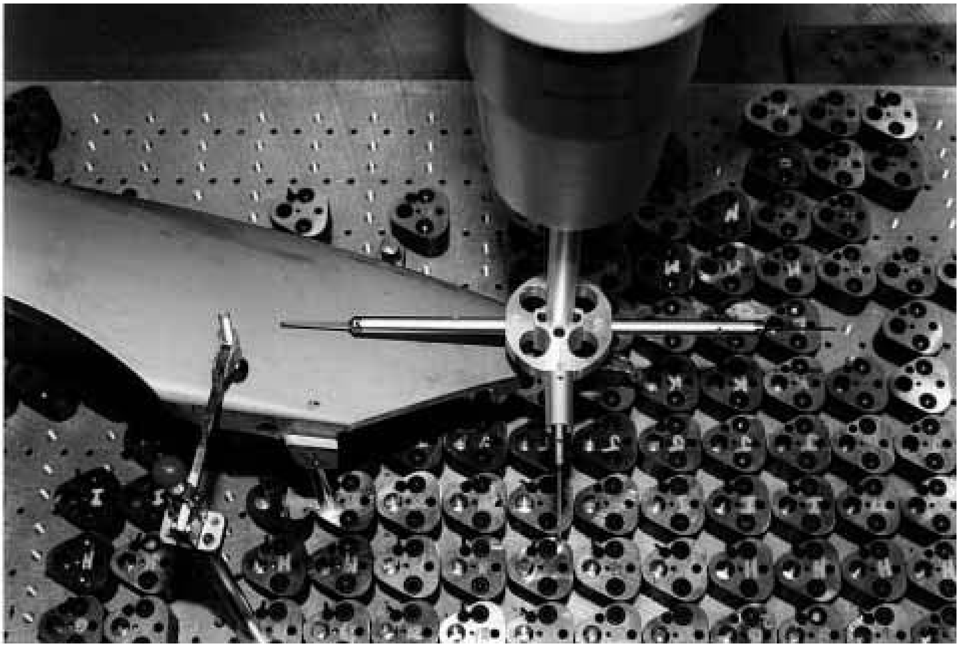
Actually, some construction appears to have started. Maybe 75 percent of this grid is covered by swarms of identical little devices called punch retainers in no discernable pattern. Ten or 12 are grouped together in one place, 20 or so in another, 6 or 8 somewhere else—maybe 40 islands on this Cartesian sea. It turns out that these groupings have evolved over six years of use, and continue to grow as new retainers are occasionally added to the collage—slow motion art.

Referring to Fig. 9.1.13, a punch retainer looks like a metal cam, sort of a triangle with rounded points, and about 4 cm (1.5 in) thick—almost as high as it is wide. You lay it down flat on its side and bolt it to the grid, and thereby establish a virtually perfect repeatable coordinate position with a quick disconnect socket.

A few of these true-position sockets have a ⅝ths diameter drill rod called a *detail* sticking straight up out of them, all with different lengths, most with a positioning detent and a spring clamp to hold a sheet metal part against the detent.

Remember that cast-iron slab? On both sides of this slab are cantilevered rails supporting two traveling coordinate measuring machines (CMMs). These two Zeiss CMMs are program driven and can each reach anywhere in the full space. Each base plate has a spherical 3-axis reference point fixed to it. The machines find these reference points in preparation for measuring relative distances thereafter.

AGILE PRODUCTION: DESIGN PRINCIPLES FOR HIGHLY ADAPTABLE SYSTEMS



(*Photography by R. Marincic.*)

FIGURE 9.1.13 Pittsburgh Universal Holding Device.

Now the phone rings. Bill picks it up, listens, grunts affirmative, hangs up, and yells to his partner, Bob. An 1985 Pontiac left front fender is coming in hot off the press and needs an immediate check.

They swing into action. Bill goes over to one of the four base plates, inserts a stiff wire into a hole in one of the retainers, and removes the unlocked detail rod. He repeats this process a dozen times in the next 45 seconds, placing each of the freed details in a blue plastic container about the size of a shoe box. We know it's 45 seconds because Bob has been looking at his watch the whole time.

Bill disappears with the container into a side room. In here is a shelving unit that holds 540 identical containers in labeled rows and columns. Bill puts the one he has into its home slot, scans slot labels until he finds the new one he needs, and returns with a new blue box in hand. This adds another 45 seconds to the time. We know because Bob has finished his first cup of coffee.

Bill heads over to the base plate while Bob heads over to the coffee pot. Bill removes one detail from the blue box and examines it. He notes the coordinate position stamped into the bottom of the holding detail and inserts it into the corresponding retainer. Within 2 minutes he has placed 14 details into their respective coordinate locations. We know it's 2 minutes because Bob's coffee break just ended—just in time for him to open the door as the fender arrives. He points the guy toward Bill.

Three and a half minutes after the phone call, Bill clamps the fender into the newly constructed holding fixture and enters the fender code into the Zeiss console. Bob presses the start button and the verification begins.

Remember that side room—the one with the 540-slot shelving? When you figure the 6-by-0.6-m (20-by-2-ft) feet-print of the shelf space and add a reasonable access aisle you find that details for 540 check-fixtures need 11 m^2 (120 ft^2). Add to that the 1-by-2-m (3-by-7-ft) holding device base plate and you have less than 14 m^2 (150 ft^2) tied up for 540 check-fixtures. The existing side room is mostly empty and could easily accommodate three times the shelf capacity.

There is nothing magic about those base plates. You can put one on a cart and take it to a press on the floor and check a part every 60 seconds—not with the Zeiss machine, with traditional gauges.

Bill and Bob invented this concept while car pooling to work together. They call it the *Pittsburgh Universal Holding Device.* They are die makers by training—and products of the innovative take-charge culture at GM's Pittsburgh plant. We caught Bob on his coffee break so that you could see that a single person is all that is needed to accomplish the actions.

Remember the part about the test? Reread the last case study again—the one about the assembly system, and then this one again. The workshop conducted at GM dissected this check-fixturing concept and cataloged the design characteristics as shown in Fig. 9.1.14. Can you find the same principles at work in the assembly system, and catalog the design characteristics similarly?

This case study is not about check-fixturing: it is about generic design principles for making any production process or business practice highly change proficient, able to turn on a dime at a moment's notice.

With close examination of the example you might notice that the contents are not pure: there is a mixture of multiple system levels. The Zeiss machines, for instance, are not really a part of the check-fixture system, but rather a part of the next higher-level system: contour verification. Similarly, the detents and clamps on the drill rods are part of a lower-level holding system. For our purpose here the distinction is not important: clear system definition becomes important when the principles are used to design new systems.

CAPTURING AND DISPLAYING PRINCIPLES IN ACTION

Virtually every business unit within a company has a few practices that exhibit high change proficiency. Typically these competencies emerge as necessary accommodations to an unforgiving operating environment. Maybe it is the ability to accommodate frequent management changes—each with a new operating philosophy. Or the production unit that automatically tracks a chaotically changing priority schedule. Or the logistics department that routinely turns late production and carrier problems into on-time deliveries. It might be a purchasing department that never lets a supplier problem impact production schedules. Or an engineering group that custom designs a timely solution for every opportunity or problem.

Every business unit has its own brand of tactical chaos it manages to deal with—intuitively, implicitly, routinely, automatically—without explicit process knowledge rooted in change proficiency. Yet at the same time, virtually every business unit today is facing strategic challenges that need this same innate competency.

What are the common underlying principles at work in these implicitly managed tactical successes? Can the enabling factors for these successes be abstracted and reapplied to other areas of the business? More important, can these successes become widespread role models that communicate these enabling factors at the depth of insight across the corporation?

Metaphors possess great power to create and communicate insight. The trick is to find a meaningful metaphor that can transfer this leveragable knowledge among a specific group of people. Workshops structured to analyze highly adaptable practices for their underlying change-proficiency enablers have been effective when they packaged their conclusions as metaphors [6].

The structured analysis process builds a model of the change-proficiency issues (proactive and reactive response requirements) and the architecture (reusable modules, compatibility framework, system engineering responsibilities). Then this architecture is examined for local manifestations of the 10 RRS design principles. The combined result produces a local metaphor model for change proficiency—*local* because it is present at the plant site and respected intuitively for its capabilities, and *metaphor model* because the analysis explicitly illuminates common underlying principles responsible for this change proficiency.

System(s)	Body-part contour check fixtures.
Framework	Base plate coordinate gridwork, 4 × 8 × 12 container shelving, ⅝ths punch retainer.
Modules	Zeiss machines, base plates, punch retainers, containers, fixture details, drill rods, detail clamps, detail detents.

Principles observed in system design	
Self-contained units: System composed of distinct, separable, self-sufficient units not intimately integrated. Base plates. Retainers. Details. Containers. Shelf slots.	*Flexible capacity:* Unrestricted unit populations that allow large increases and decreases in total unit population. Base plate can be extended to any size. Unlimited shelving can be added. Details for large/complex fixture could occupy multiple containers.
Plug compatibility: Units share common interaction and interface standards, and are easily inserted/removed. Standard retainers bolted to base plate. ⅝ths drill rods inserted in retainers. Common form factor containers in shelving slots. Coordinate gridwork.	*Unit redundancy:* Duplicate unit types or capabilities to provide capacity fluctuation options and fault tolerance. Base plates. Blue containers. Shelf slots. Retainers. Multiple CMM machines.
Facilitated reuse: Unit inventory management, modification tools, and designated maintenance responsibilities. "Zeiss Room" personnel are responsible for obtaining/maintaining: Pool of common retainers. Common off-the-shelf shelving. Pool of common containers. New details and base plates.	*Evolving standards:* Evolving, open system framework capable of accommodating legacy, common, and completely new units. Base plate can be any size or shape. Retainers are installed as needed when needed. Can use with traditional layout table and gauges as well as CMMs.
Nonhierarchical interaction: Nonhierarchical direct negotiation, communication, and interaction among system units. None noted.	*Distributed control and information:* Units respond to objectives; decisions made at point of knowledge; data retained locally but accessible globally. Coordinates stamped on rods.
Deferred commitment: Relationships are transient when possible; fixed binding is postponed until immediately necessary. Reference sphere provides real-time zero point. Rods inserted in retainers when fixture needed. Retainers bolted to plates as needed.	*Self-organizing unit relationships:* Dynamic unit alliances and scheduling; open bidding; and other self-adapting behaviors. Reference sphere provides real-time zero point.

FIGURE 9.1.14 Pittsburgh Universal Holding Device: systems design.

For example, the local metaphor model shown in Fig. 9.1.15 synopsizes the underlying principles at work in the case study of the just-in-time assembly line, and graphically depicts the concept of assembling reconfigurable systems from reusable modules. When coupled with the case study description, this tool can be employed outside the local environment as well.

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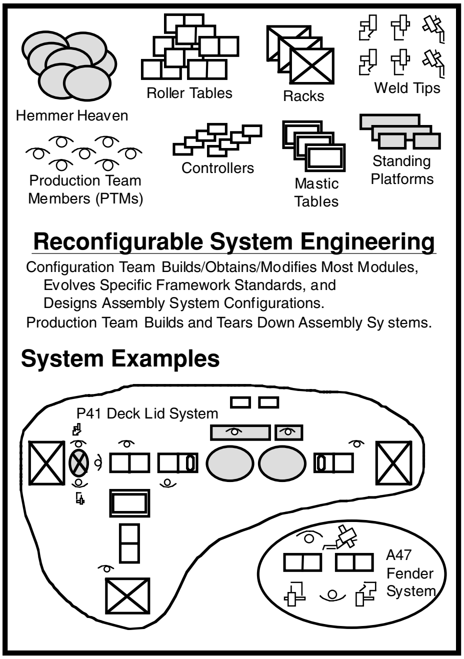
Change Proficiency

Key Proactive Issues:
Creation:
  Assembly line construction
Improvement:
  Space productivity
Migration:
  New performance metrics
Addition/Subtraction:
  PTM staff changes

Key Reactive Issues:
Correction:
  Labor/mgmnt relations
Variation:
  System setup time
Expansion:
  Space availability
Reconfiguration:
  Flexibility culture


Hemmer Heaven
Roller Tables
Racks
Weld Tips
Production Team Members (PTMs)
Controllers
Mastic Tables
Standing Platforms
Reconfigurable System Engineering
Configuration Team Builds/Obtains/Modifies Most Modules,
Evolves Specific Framework Standards, and
Designs Assembly System Configurations.
Production Team Builds and Tears Down Assembly Sy stems.
System Examples
P41 Deck Lid System
A47 Fender System

Reusable Modules:
- Cross-trained PTMs (production team members)
- Roller tables
- Weld tips
- Hemmers
- Controllers
- Mastic tables
- Racks
- Standing platforms
- And others

Compatibility Framework:
- Overhead support grid
- Physical space
- Utility standards
- System compatibility rules
- Unit compatibility rules
- Plant flexibility culture
- Local union contract

FIGURE 9.1.15 Local metaphor model: small-lot assembly lines.

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BIOGRAPHY

Rick Dove is chairman of Paradigm Shift International (www.parshift.com), an enterprise research and guidance firm. In 1991 he cochaired the 21st-Century Manufacturing Enterprise Strategy project at Lehigh University—the industry-led effort responsible for today's interest in agility. Subsequently, as the Agility Forum's first director of Strategic Analysis, he established its initial research agenda and industry involvement structure. He has developed structured assessment and maturity-modeling concepts and processes used for strategic planning and analysis of change proficiency, and for guiding management through a knowledge development and transfer process. His book, *Response Ability—Understanding the Agile Enterprise,* provides the first analytical techniques and models for agile enterprise assessment and strategy development.

Source: MAYNARD'S INDUSTRIAL ENGINEERING HANDBOOK

CHAPTER 9.2

SCHEDULING AND INVENTORY CONTROL OF MANUFACTURING SYSTEMS

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This chapter addresses both the planning and control of manufacturing systems.* It is important to note that entire books have been written about many of the topics covered in this chapter. The chapter therefore cannot provide complete stand-alone coverage of these topics. The approach that has been used is to provide the reader an overview of a wide range of topics related to production planning and inventory control. Where more specific information is desired, the reader may consult additional resources cited in each of the chapter sections and at the end of this chapter.

TYPES OF INVENTORY SYSTEMS

The concept of lot sizing addresses two questions with regard to parts that are either made or purchased: (1) When should the order be placed? (2) How many parts should be ordered?

Two families of lot sizing techniques exist. The first family is called *reorder point lot sizing systems.* Reorder point methods are used for parts whose demands are known to be independent of one another. Department stores, grocery stores, and stores selling replacement automobile parts are examples of organizations that would use reorder point inventory systems.

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† Deceased.

* Much of this chapter has been adapted from two sources. The first is from a chapter entitled "Planning and Control of Manufacturing Systems," which appeared in the previous edition of this *Handbook.* The second source is a chapter entitled "Production and Inventory Control," which appears in *Electronics Manufacturing Processes* by Landers, Brown, Fant, Malstrom, and Schmitt, published in 1994 by Prentice-Hall. Material from this second source has been adapted with the written permission of the publisher.

In a manufacturing environment, assembly relationships usually exist between a final assembly that is shipped to the customer and all of its component parts. If the demand for final assemblies is known, it defines corresponding demands for all component parts in the final assembly.

Reorder point inventory systems do not lend themselves to these types of production situations. Since the demands for end items and their components are functionally related, availability of component parts at the time they are needed in the manufacturing process cannot be ensured by reorder point systems. A second family of inventory models, called *explosion-based inventory systems,* is therefore used to address question of lot sizes.

Explosion-based inventory systems use lot sizing heuristics. Many of these heuristics are based on reorder point methods. The following pages explain both explosion-based and reorder point lot sizing methods.

EXPLOSION-BASED INVENTORY SYSTEMS

Explosion-based inventory systems rely on requirements planning. *Requirements planning* may be defined as the management of raw materials, components, and subassemblies to ensure that these products are produced in sufficient quantity to satisfy the requirements for end items.

Master Scheduling

End items are scheduled to be produced in accordance with the *master schedule,* which is a forecast, by time period, of the anticipated demand for production end items. Vollman, Whybark, and Berry [1] define *master scheduling* as the anticipated build schedule for manufactured end products. The master schedule is not the specific result of a sales forecast. It is a statement of scheduled production that is likely to satisfy anticipated demand. Anticipated levels of sales may be regarded as critical inputs in determining master schedules. However, the master schedule also takes into account both limitations in factory capacity and the need to utilize such capacity as fully as possible [1].

The master schedule indirectly determines the demands and related procurement schedules for all production components contained in the end items being produced. For example, a production schedule of 100 automobiles per month infers the need for prior procurement of 500 tires per month (four tires per car plus one spare). This procurement needs to be completed in advance of the car being assembled so the tires are available to mount on the car at the time it is built. An explosion-based inventory system known as *material requirements planning* (MRP) facilitates the determination of procurement and production of production components. This system will be discussed later in this chapter.

Vollman, Whybark, and Berry [1] define a variety of master scheduling techniques. One of the more detailed approaches is the *time-phased record* approach. With this procedure, cumulative production and the cumulative sales forecasted are plotted over a specified planning horizon. Actual and forecasted sales are compared with one another. With this method, a backlog of orders may exist. In other words, the demand for end items of production may exceed the supply available in any period. The master schedule, forecasted sales, and actual sales are compared with one another. This comparison permits end items to be committed for shipment to customers in future time periods in the planning horizon.

Figure 9.2.1 shows a 12-month planning horizon. It is now January 1. An on-hand balance of 40 units has been carried over from the preceding month. The entries in Fig. 9.2.1 are computed in the following manner. Orders of five units per month have been promised for each of the first four months. These orders must be satisfied in addition to the sales forecast. For January the total demand is the 10 units from the sales forecast plus the 5 units previously promised. This leaves 40 − 15 = 25 units available at the end of January. Since 15 total units have been promised for February, March, and April, only 25 − 15 = 10 units are available to promise at the end of January.

	J	F	M	A	M	J	J	A	S	O	N	D
Forecast	10	10	10	10	10	20	20	20	20	20	20	20
Orders	5	5	5	5								
Available	25	10	55	40	30	10	50	30	10	50	30	10
Available to promise	10	0	50				50			50		
MPS			60				60			60		

On hand 1/1 = 40

FIGURE 9.2.1 Time-phased record.

The quantity available at the end of any period can be determined from the relationship

$$A_i = A_{i-1} + \text{MPS}_i - F_i - O_{pi} \tag{9.2.1}$$

where A_i = stock available at the end of period i
MPS_i = quantity scheduled for production in period i by the master schedule
F_i = forecasted demand for period i
O_{pi} = order quantity of units previously promised for delivery during period i

The amount available to promise in any period is defined by Eq. (9.2.2).

$$\text{ATP}_i = A_i - \sum_{j=i+1}^{n} O_{pj} \tag{9.2.2}$$

where ATP_i = amount available to promise in period i

Orders are generated on the master schedule in the following manner. A total of 10 units is carried forward from the end of February. The total demand for March is 15 units—10 units from the sales forecast and 5 units that have been previously promised. The 10 units available are not sufficient to satisfy this demand. The master schedule therefore calls for an additional 60 end items to be available by the beginning of March. Applying Eq. (9.2.1) yields the amount available at the end of this month (45 units). Equation (9.2.2) yields a value of 50 units available to promise during March.

All other entries in Fig. 9.2.1 are determined in this manner. The reader should note that the MPS quantity of 60 is arbitrary. Methods for determining actual lot sizes will be discussed later. Readers desiring more detailed information on the subject of master scheduling should consult Refs. 1 to 4.

Material Requirements Planning

The most popular explosion-based inventory system is called *material requirements planning* (MRP). The most substantive treatment of MRP in early technical literature has been given by Orlicky [3]. MRP examines the assembly relationships between the component parts of an end item being produced. These relationships are used to generate both production and purchase schedules for "make" and purchased parts. These schedules ensure that sufficient components and subassemblies will be produced at the right time and in the right quantities to satisfy the forecasted demand for end items.

A part explosion diagram is also called a *bill of materials.* The diagram indicates the what-goes-into-what relationship of a manufactured end item. Each discrete part or subassembly is indicated by a separate node in the diagram. A sample node is illustrated in Fig. 9.2.2. As indicated in this illustration, the upper half of the node contains the part number of the component or assembly. The lower left portion of the node indicates the number of the part or subassembly required at the next higher assembly level. Finally, the lower right portion of the node indicates whether the part is to be made or purchased.

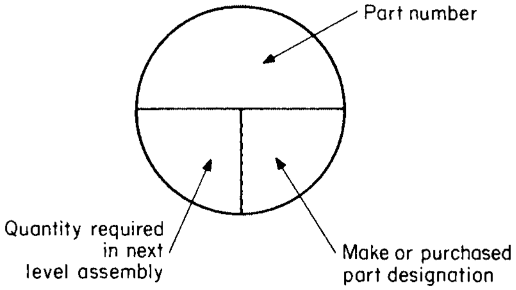

Part number
Quantity required in next level assembly
Make or purchased part designation

FIGURE 9.2.2 Notation for part explosion diagram.

A sample part explosion diagram is illustrated in Fig. 9.2.3. The diagram shows the component parts for a microcomputer to be fabricated by an electronics manufacturing facility. The reader should note that four distinct assembly levels exist and that the nodes corresponding to each assembly level are arranged in columns on the diagram. Required make or purchase lead times are indicated to the right of each node, in most cases on the connecting assembly links of the diagram.

Generation of MRP Tables

The MRP logic is manifest in tables that specify the production schedule and inventory policy or each node in the bill of materials. All production schedules are a function of time. The time periods used in generation of these schedules are called *time buckets.* Prevailing current practice is for MRP to use bucketless logic; however, data is usually displayed in time buckets that are either in weeks or months. Each production schedule for a component or assembly consists of a table with four sets of entries:

1. *Gross requirements* (GR). The amount of the parts or components required to satisfy the master schedule in any time bucket.
2. *Scheduled receipts* (SR). An order of quantity Q units scheduled to arrive at the beginning of the time bucket. This order was placed LT time buckets ago, where LT is the lead time for the part or component.
3. *On hand* (OH). The on-hand balance of the part or component that remains at the end of the time bucket. The on-hand balance for any period t is given by Eq. (9.2.3).

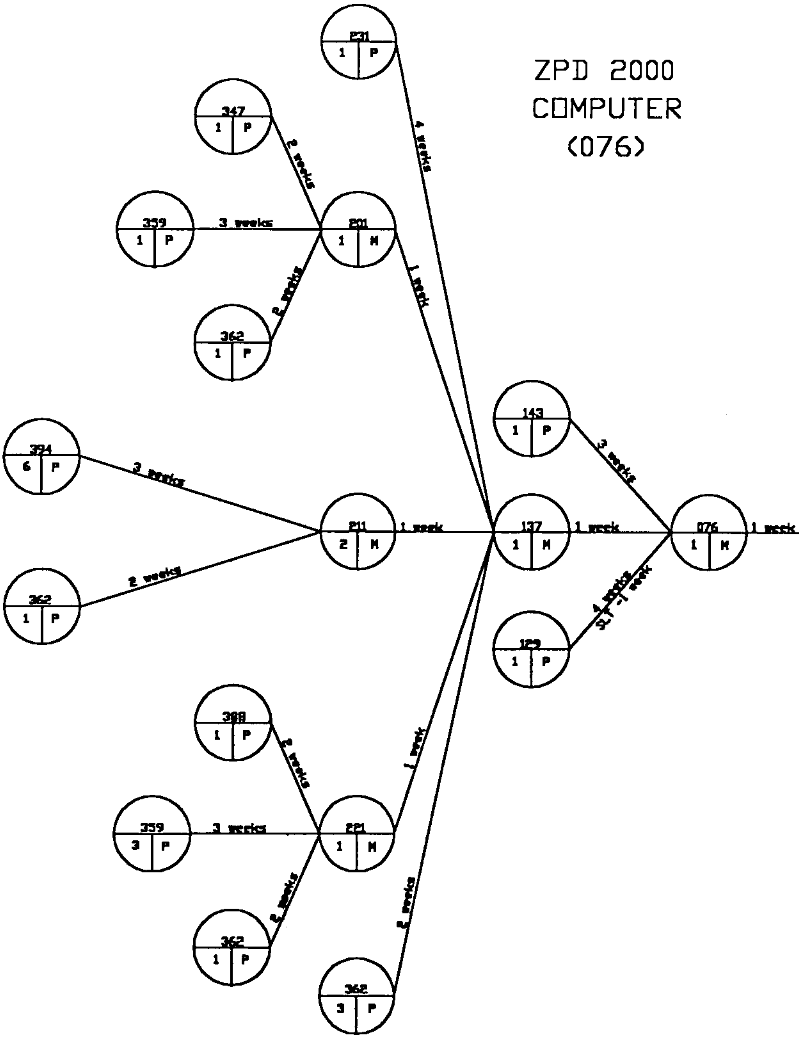
$$OH_t = OH_{t-1} + SR_t - GR_t \tag{9.2.3}$$

where OH_t = parts on hand at the end of period t
SR_t = scheduled receipts that are to arrive at the beginning of period t
GR_t = gross requirements to be satisfied in period t

4. *Planned orders* (PO). An order of size Q is initiated during period (time bucket) t. This order will arrive at the beginning of period (t + LT) as a scheduled receipt.

Suppose the master schedule for the end item shown in Fig. 9.2.3 is as shown in Fig. 9.2.4. The MRP logic may be applied in the following manner. From Fig. 9.2.4, 150 end items must be available to ship at the beginning of period 20. From Fig. 9.2.3, it is apparent that the lead time for end items (part 076) is one week. This time allows for the final assembly of this part, which consists of parts 143, 137, and 129.

We begin by determining the gross requirements. Since a schedule for end items is desired, the gross requirements row of the table is merely the master schedule from Fig. 9.2.4. The result is shown in Fig. 9.2.5.


ZPD 2000
COMPUTER
(076)
231
1
P
4 weeks
347
1
P
2 weeks
359
1
P
3 weeks
201
1
M
362
1
P
2 weeks
1 week
143
1
P
3 weeks
394
6
P
3 weeks
211
2
M
1 week
137
1
M
1 week
076
1
M
1 week
362
1
P
2 weeks
129
1
P
4 weeks
SLT -1 week
388
1
P
2 weeks
359
3
P
3 weeks
221
1
M
1 week
362
1
P
2 weeks
362
3
P
2 weeks

```
076    ZPD 2000
        143   Video Display Terminal (VDT)
        129   Keyboard
        137   Processing Unit
               231   Casing
               201   I/O Board
                      347   I/O Switch
                      359   Rom Chip
                      362   Switch

               211   Memory Board
                      394   Ram Chip
                      362   Switch

               221   Arithmetic Board
                      388 Microprocessor Chip
                      359   Rom Chip
                      362   Switch
               362   Switch
```

FIGURE 9.2.3 Example part explosion diagram.

Period	20	21	22	23	24	25	26	27	28	29	30
Demand	150	220	200	200	250	260	160	220	220	200	180

FIGURE 9.2.4 Master schedule for ZPD 2000 computers.

We will assume that a separate order is placed for each period's demand. (This lot sizing decision is arbitrary, and specific MRP lot sizing methods will be described later.) The order schedule then becomes the planned order row of the table. Since the required lead time for the part is one week and a separate order is placed for each period, the planned order row is identical to the gross requirements row, but starts one week earlier in time. (This example assumes a previous balance of 150 end items from period 19.)

Refer again to Fig. 9.2.5. The scheduled receipts row depicts the arrival of each order one week after it is placed. Since the scheduled receipts exactly equal the gross requirements for each period, all end-of-period on-hand balances are zero.

Consider now the generation of a procurement schedule for the video display, part 143. From Fig. 9.2.3 it is apparent that the video display is purchased and requires a lead time of three weeks.

We begin by determining the gross requirements. For any component part, the gross requirements may be determined by considering the relationship between parent and component nodes in the part explosion diagram. A *component node* is any node that goes into a node at the next higher assembly level in the part explosion diagram. The node that the component node goes into is called the *parent node.*

Refer to Fig. 9.2.3. Part 076 is a parent node for the component nodes corresponding to parts 143, 137, and 129. Similarly, part 137 is a parent node for parts 231, 201, 211, 221, 362, and so on. The gross requirements for any component node may be defined as a function of the planned orders of the parent node in accordance with Eq. (4).

$$\mathrm{GR}_c = \mathrm{PO}_p(Q_g) \tag{9.2.4}$$

where GR_c = gross requirements of the component node
PO_p = planned orders of the parent node
Q_g = goes into quantity between the component node and the parent node

From Fig. 9.2.3, the goes into quantity between part 076 and part 143 is 1. This means that one video display is required at the next higher assembly level. The gross requirements for the video display is then the planned orders for part 076 (from Fig. 9.2.5) times 1. This is shown in Fig. 9.2.6.

Suppose a total of 500 video displays are in stock at the end of period 19. The on-hand balances at the end of each period may be obtained by subtracting the gross requirements for each period from the initial stock balance. This is shown in Fig. 9.2.6. Completing these computations shows that a balance of 80 video displays is projected for the end of period 21. Further inspection shows that this balance is not sufficient to satisfy the scheduled demand for period 22, in this case, 200 units.

MRP does not allow part shortages to occur. It is therefore necessary to schedule an order to arrive at the beginning of period 22. Suppose this order size is 500. (Again, the selection of this lot size is arbitrary and is used for example purposes only.) The purchase lead time for

Period	19	20	21	22	23	24	25	26	27	28	29	30
Gross required		150	220	200	200	250	260	160	220	220	200	180
Schedule required			220	200	200	250	260	160	220	220	200	180
On hand	150	0	0	0	0	0	0	0	0	0	0	0
Planned order		220	200	200	250	260	160	220	220	200	180	

FIGURE 9.2.5 MRP table for ZPD 2000 computer P/N 076.

Period	19	20	21	22	23	24	25	26	27	28	29	30
Gross required		220	200	200	250	260	160	220	220	200	180	
Schedule required				500		500		500			500	
On hand	500	280	80	380	130	370	210	490	270	70	390	
Planned order	500		500		500			500				

FIGURE 9.2.6 MRP table for video display P/N 143.

video displays is three weeks. To arrive in period 22, the order would have to be placed in period 19. A planned order in this amount is therefore shown for this period.

Applying Eq. (3) yields the remaining on-hand balances. The on-hand balance at the end of period 23 is 130. This is not sufficient to satisfy the demand for period 24 (260 units). It is thus necessary to schedule another order to arrive at the beginning of period 24 to prevent a shortage from occurring. To arrive in period 24, this order must be placed in period 21. An order size of 500 units is again used. Applying this logic to the remaining entries in Fig. 9.2.6 results in additional orders that must be scheduled to arrive in periods 26 and 29. These orders are placed in periods 23 and 26, respectively.

This procedure may be used to generate production or procurement schedules for all of the remaining nodes in Fig. 9.2.3. Readers desiring a more detailed explanation of MRP logic for all levels in the bill of materials are urged to consult Ref. 5. The previous example is intended to present the reader with an overview of MRP inventory logic. Readers desiring a more detailed description of MRP should consult Refs. 1 to 3 and 6 to 13.

MRP Lot Sizing Heuristics

Lot sizing in an MRP environment is equivalent to determining how many periods of gross requirements to combine into a planned order. The lot sizes used in the preceding example were purely arbitrary. They were selected to keep inventory levels low. This procedure tends to minimize the cost of keeping purchased parts, finished goods, and work-in-process inventory in stock. This section describes MRP lot sizing heuristics. These heuristics can be used to determine MRP order sizes. The order sizes tend to minimize the total costs of setups/orders and the costs of carrying inventory in stock.

When more than one level of the part explosion diagram is considered, it is usually not possible to prove the optimality of MRP lot sizing methods. MRP lot sizing heuristics are based on reorder point lot sizing methods. These techniques are addressed in a later section of this chapter.

The effectiveness of MRP lot sizing methods has been thoroughly investigated by simulating different types of rules with a variety of part explosion structures and demand patterns. The following subsections overview some typical MRP lot sizing methods. The comparative effectiveness of these rules in terms of total annual inventory cost is also described.

Lot-for-Lot Heuristic. The *lot-for-lot* (LFL) *heuristic* specifies that a separate order is placed for each period or time bucket. No periods of demand are combined. The order size is merely the gross requirement for the period in question.

The LFL method typically has high order costs since separate orders are placed for each period with a nonzero demand. Carrying costs are minimized by this approach because the stock is always used in the period in which it arrives. The LFL method most closely represents the just-in-time (JIT) order philosophy, which will be described later.

Economic Order Quantity Heuristic. The *economic order quantity* (EOQ) *heuristic* applies the economic order quantity logic of reorder point inventory systems. The EOQ approach attempts to select the lot size that minimizes the sum of both order and carrying costs. This method assumes that demand from period to period is relatively constant.

The EOQ heuristic is based on the equation used in reorder point lot sizing systems described later in this chapter. Each time it is necessary to place an order, Eq. (5) in this chapter is used to determine the order size. If the order size happens to be less than the gross requirement for the period in question, the order size is increased to a level just large enough to prevent shortages from occurring. When an initial stock balance exists, the annual demand R in Eq. (5) is reduced by the amount of the initial stock balance. Carrying costs for the initial inventory are added to the total annual inventory cost.

Periodic Order Quantity Heuristic. The *periodic order quantity* (POQ) *heuristic* uses the EOQ logic to determine the optimal time interval between orders. An order is then initiated just large enough to cover the demand that is scheduled to occur over this time interval. Time periods in the interval are totaled in such a way that no order is scheduled for receipt during a period that has zero demand. This avoids incurring unnecessary carrying costs. This method responds well to demand patterns with wide fluctuations.

Least Unit Cost Algorithm. The *least unit cost* (LUC) *algorithm* computes for various order sizes the cost per unit chargeable to orders/setup and storage. The order size that minimizes the total cost per unit is selected.

Least Total Cost Algorithm. The *least total cost* (LTC) *algorithm* is also based on EOQ logic. It may be shown that the cost minimum corresponding to the optimal order size of Eq. (5) occurs at the point where the annual order costs and the annual carrying costs equal one another. The LTC algorithm analyzes the gross requirements over a specified planning horizon. Various order quantities are evaluated. The order quantity that makes the resulting order and carrying costs most closely equal to one another is selected.

Part Period Balancing Algorithm. The *part-period balancing* (PPB) *algorithm* is very similar to the LTC approach to lot sizing. The primary difference between the two methods is an adjustment look-ahead/look-back routine. This feature prevents inventory intended to cover peak period demands from being carried in stock for long periods of time. It also helps orders from being keyed to periods with low requirements.

Silver-Meal Algorithm. The *silver-meal* (SM) *algorithm* is computationally more robust than the methods previously described. The method is based on selecting the order quantity that will minimize the cost per unit time over the time periods during which the order quantity lasts. This is a search on a time variable defined over the order quantity under the assumption that all inventory needed during a period must be available at the beginning of that period. This assumption of stock availability also holds for all of the previously described algorithms and heuristics.

Wagner-Whitin Algorithm. The *Wagner-Whitin* (WW) *algorithm* uses an optimizing procedure that is based on a dynamic programming model. It evaluates all possible combinations of orders to cover requirements in each period of the planning horizon. Its objective is to arrive at an optimal ordering strategy for the entire requirements schedule.

The algorithm does minimize the total cost of setup and carrying inventory, but only for the assembly level of the part being considered. The algorithm has the disadvantage of a high computational burden due to its mathematical complexity.

Comparative Performance of Heuristics. The comparative performance of lot sizing heuristics has been studied in detail over the last 15 years. Results of key studies have been documented by Choi, Malstrom, and Classen [9,10], Choi, Malstrom, and Tsai [8], Heemsbergen and Malstrom [11], and Taylor and Malstrom [14]. Digital simulation has been used to simulate the heuristics under a variety of part explosion and demand conditions. More recent studies have evaluated larger part explosion product structures with increasing amounts of actual manufacturing data as inputs.

Of the heuristics previously described, the consistent best performer has been the periodic order quantity (POQ) rule. Other rules that have performed well include the least total cost (LTC) and least unit cost (LUC). Marginal rules on the basis of performance have included the economic order quantity (EOQ), Wagner-Whitin (WW), and Silver-Meal (SM) methods. The lot-for-lot (LFL) rule has been consistently the worst-performing heuristic in all evaluations. Total annual inventory costs associated with this method are 3 to 20 times more expensive than the best-performing rules in the variety of simulation studies that have been conducted [9,11,14,15].

The feature that has consistently distinguished good rules from the ones that are not cost-effective has been the order policy structured for end item products. Those rules that trigger frequent separate orders for end items incur annual setup or order costs that are extremely high. The increase in these costs is not completely offset by the corresponding lower carrying costs that are obtained.

This conclusion has some interesting implications for just-in-time (JIT) inventory systems. JIT order policies are most closely represented by the lot-for-lot (LFL) heuristic. This method has historically been the least effective of the rules evaluated. Malstrom [16] and Mirza and Malstrom [13] have determined that setup or order costs must be reduced to levels equal to $1/100$ or less of the corresponding carrying cost for each node before the performance of the LFL heuristic begins to significantly improve relative to other lot sizing methods.

It is questionable whether this reduction in both setup and order costs is always attainable when JIT policies have been implemented. Burney and Malstrom [17–19] have stated that such potential increases in order costs have the potential to negate many of the possible savings attainable with JIT policies. JIT inventory procedures are discussed in greater detail later in this chapter.

REORDER POINT INVENTORY SYSTEMS

Unlike explosion-based inventory systems previously described, reorder point systems do not consider assembly relationships depicted by the parts explosion diagram. *Reorder point systems* (ROP) are used for separate parts whose demand is known to be functionally independent of one another. Spare parts and inventories in grocery stores and other retail outlets are example applications for reorder point inventory systems.

A variety of reorder point lot sizing methods exist. Most of the mathematically straightforward models are based on a number of restrictive assumptions. Many of these assumptions are not true in practice. As these assumptions are relaxed, the computational complexity of the lot sizing models increases significantly. The assumptions are summarized as follows:

- Annual demand is constant and is known exactly.
- Orders are received instantly.
- Lead time is known and is constant.
- Order costs are known and are independent of order size.
- Purchase price is constant. Price may vary with the order size.
- Storage capacity is available to store up to one year's demand of an item.

Entire texts have been written on lot sizing models. It is therefore not feasible to cover all of them in detail here. The approach used will be to summarize popular methods in increasing order of mathematical complexity. The assumptions associated with each method will be summarized. Mathematical derivations of each approach will not be presented. However, lot sizing formulas will be included, where appropriate, to assist the casual reader in selecting the appropriate method.

Notation

In describing lot sizing notation, it is necessary to address the concept of inventory cycles. This is best accomplished by reviewing the inventory stock level of a given part over time. This relationship is illustrated in Fig. 9.2.7. The first inventory cycle begins by assuming that an order in the amount of Q units has just been received. A constant demand is assumed, so the stock level is depleted at a linear rate.

Initially, stock shortages are assumed not to occur. A second order is placed when the stock level reaches Q_{ro} units, the reorder point. This value defines the part's lead time (LT) since a new order must arrive exactly when the stock level for the part reaches zero. The maximum stock level is Q units; the minimum level is zero. It follows that the average stock level during the inventory cycle time t is $Q/2$ units.

A standardized set of notation for lot sizing has yet to be developed. Commonly used notation in many texts is similar to the following and will be used throughout the remainder of this chapter:

TIC = total inventory cost
TIC_o = optimal or minimum TIC for a given lot size
Q = lot size or order quantity
Q_o = optimum lot size corresponding to TIC_o
R = annual demand in units per year
C_H = holding cost in dollars per unit-year
C_P = order cost in dollars per order
C_S = shortage cost in dollars per unit short-year
Q_{ro} = reorder point in units
LT = lead time
B = buffer or safety stock level
I = inventory level
S = sales price in dollars per unit

Classical EOQ Model

The classical economic order quantity (EOQ) model was first developed by Harris [20] in 1915. All of the preceding restrictive assumptions apply for the EOQ model. In addition, part shortages are not allowed.

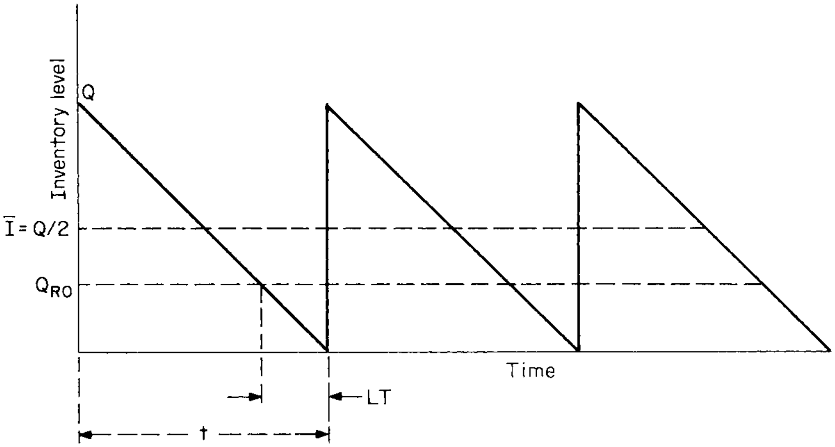


FIGURE 9.2.7 Inventory cycles and notation.

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The model determines the order quantity that minimizes the sum of annual order costs and annual carrying costs for the part being ordered. The optimal order quantity is given by the following equation:

$$Q_o = (2RC_P/C_H)^{1/2} \tag{9.2.5}$$

The corresponding minimum total annual inventory cost is given by Eq. (6).

$$\text{TIC}_o = (2RC_PC_H)^{1/2} \tag{9.2.6}$$

It should be noted that Eq. (6) is valid only when $Q = Q_o$.

EOQs with Shortages. It is possible to adapt the previous model to allow it to address situations where stock shortages occur. Consider the inventory pattern shown in Fig. 9.2.8. In this illustration, the maximum inventory balance during any cycle is $I_{\max}$. The period of positive inventory balance is t_1. During period t_2, shortage in the amount of $Q - I_{\max}$ units accrues. An order of size Q is needed to restore the inventory to its previous level of $I_{\max}$. Q is the order size. Of this total, $Q - I_{\max}$ units are effectively backordered. The optimal order size and corresponding minimum inventory cost are given by Eqs. (9.2.7) and (9.2.8).

$$Q_o = (2RC_P/C_H)^{1/2}\,[(C_H + C_S)/C_S)]^{1/2} \tag{9.2.7}$$

$$\text{TIC}_o = (2RC_PC_H)^{1/2}\,[(C_S/(C_H + C_S)]^{1/2} \tag{9.2.8}$$

Readers should be advised that Eq. (9.2.8) is valid only when $Q = Q_o$.

EOQs with Price Breaks. This model applies the EOQ methodology to situations where price breaks occur. Generally, vendors will offer products at discounted prices when larger

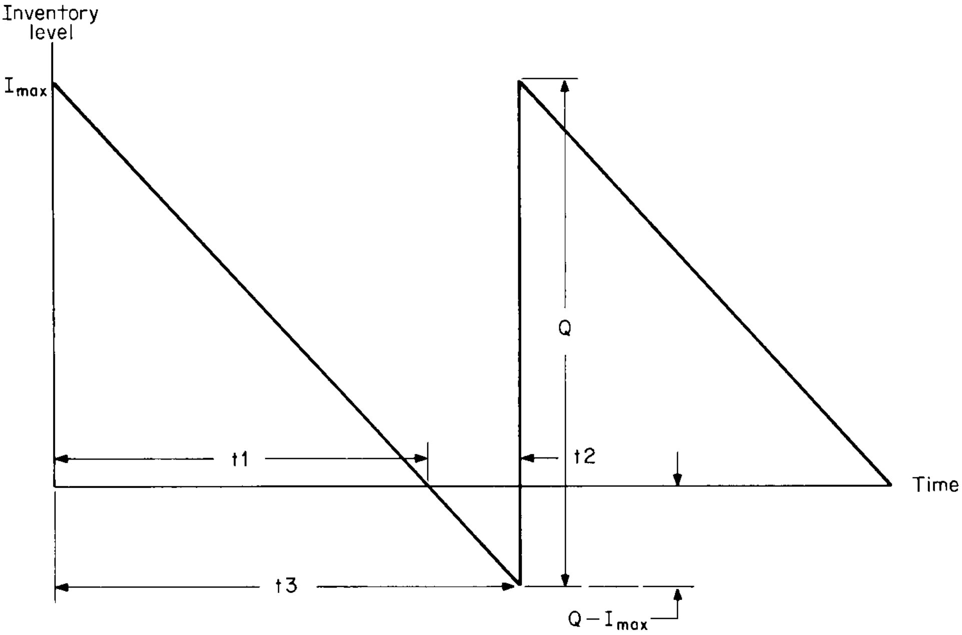

FIGURE 9.2.8 EOQ with shortages.

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orders are placed. For this model, it is necessary to define a new carrying cost parameter F_H. F_H defines holding costs as a fixed percentage of the annual inventory value of the part being stocked. The optimal and total annual inventory costs for this model are defined by Eqs. (9.2.9) and (9.2.10). In these equations, S is the sales price in dollars of the item being stocked.

$$Q_o = (2RC_P/SF_H)^{1/2} \tag{9.2.9}$$

$$\text{TIC} = C_PR/Q + SR + SF_H(Q/2) \tag{9.2.10}$$

Equations (9.2.9) and (9.2.10) are applied in the following manner to solve for the optimal lot size. For an order situation with price breaks, each price must have a specific quantity interval. The quantity intervals may not overlap. The price per unit must decrease as the order quantity intervals increase in size.

Equation (9.2.9) is used to solve Q for all values of S that apply for the quantity intervals in question. For each computation, the user must check to ensure that the value of Q obtained falls within the quantity interval for which the value of S used in the computation applies. Equation (9.2.10) is used to compute the total inventory cost associated with the quantity interval.

If Eq. (9.2.9) yields a value of Q lower than the lowest value of the quantity interval, the obtained value of Q is not used in the computation. Instead, the lowest value of Q in the quantity interval for which S applies is selected. This value is substituted in Eq. (9.2.10) to obtain the total inventory cost.

If the obtained value of Q is greater than the largest value in the quantity interval, the obtained value of Q from Eq. (9.2.9) is again not used. Instead, the largest value of Q in the quantity interval for which S applies is selected. This value is substituted in Eq. (9.2.10) to obtain the total inventory cost.

The preceding calculations are performed for all different values of S and their corresponding quantity intervals. An inventory cost associated with each value of S is determined. The optimal order policy is that quantity (and value of S) that has the smallest total inventory cost.

Economic Production Quantity Model

The economic production quantity (EPQ) model applies the EOQ logic to parts that are made, as opposed to those purchased from an outside vendor. The production situation is depicted in Fig. 9.2.9. A part is produced internally at the rate of p units per day for a period

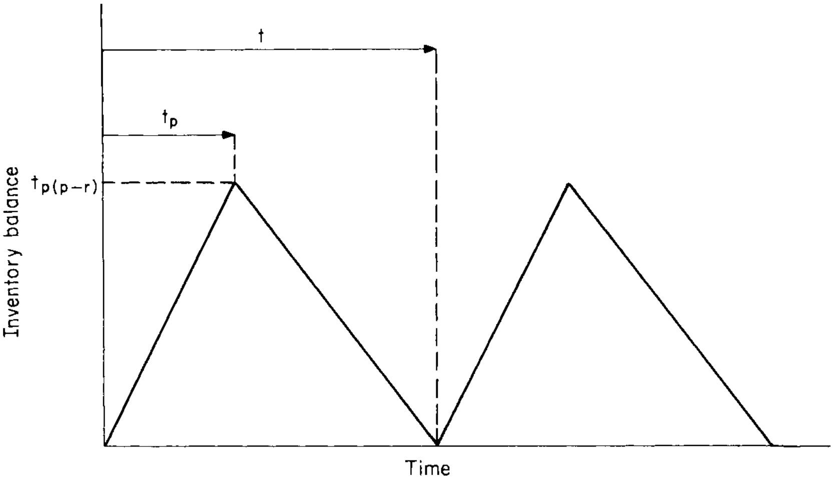

FIGURE 9.2.9 Economic production quantity stock levels.

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of t_p days. If the daily demand for the part is r units per day, then the inventory balance increases by $(p - r)$ units for each day of production.

At the end of the production period there exists an inventory balance of $t_p(p - r)$ units. This stock level is depleted at the rate of r units per day for the remainder of the inventory cycle. When the stock balance reaches zero, production of the part is again initiated, and the inventory cycle repeats. The optimal order size and corresponding inventory cost are given by Eqs. (9.2.11) and (9.2.12).

$$Q_o = \{2RC_P/[C_H(1 - r/p)]\}^{1/2} \tag{9.2.11}$$

$$\text{TIC}_o = [2RC_PC_H(1 - r/p)]^{1/2} \tag{9.2.12}$$

As before, Eq. (9.2.12) is valid only when $Q = Q_o$.

Variable Demand, Constant Lead Time Models

The preceding inventory models have all assumed that the demand for the product is constant during both the lead time and the total inventory cycle. This is rarely true in practice. Consider the situation shown in Fig. 9.2.10. The demand from the beginning of each order cycle occurs at some average rate, $\bar{D}$. While the stock is shown to be depleted at a constant rate during the inventory cycle, it will actually vary in accordance with some statistical distribution until the reorder point Q_{ro} is reached.

For analysis purposes, it is not necessary to know the demand variation prior to the time Q_{ro} is reached. The approach concentrates on determining demand variation during the lead time (LT). LT is assumed to be constant.

The variance in the demand during the lead time is accounted for by carrying a buffer or safety stock. If the lead time demand continues at its average rate, the stock balance will be depleted exactly to zero by the time the next order arrives. The buffer stock is carried to sat-

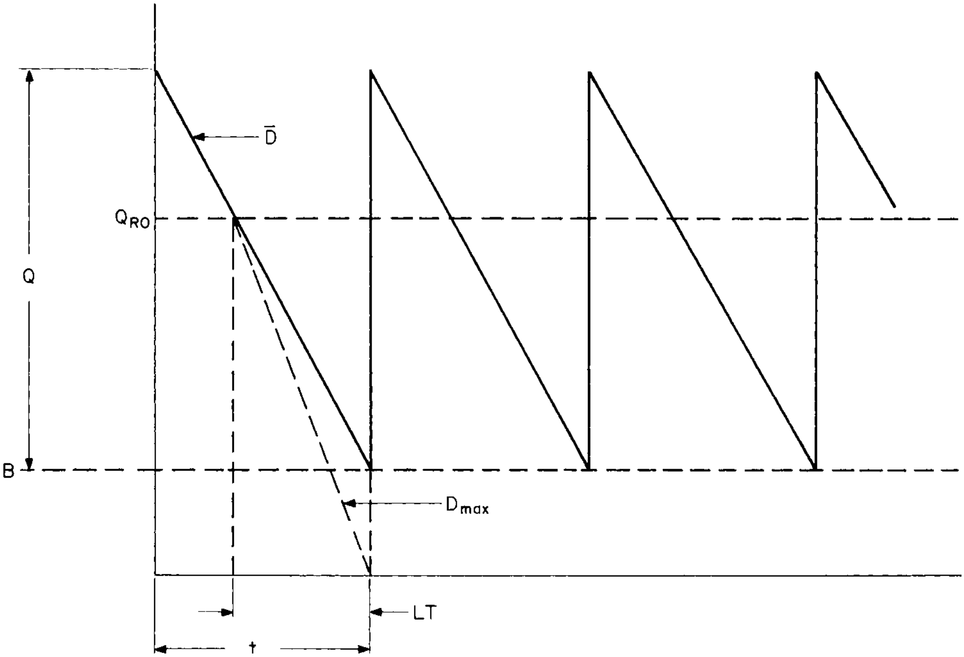

FIGURE 9.2.10 Variable demand constant lead time stock levels.

isfy lead time demand up to a rate of $D_{\max}$ units per day. The level of $D_{\max}$ selected in determining the buffer stock level B determines the service level associated with the order policy. The service level is that percentage of the time during any order cycle that a stockout will not occur. The higher the service level, the higher the level of buffer stock.

Variable demand, constant lead time models are of two types: *backorder* and *lost sales*. Backorder models assume that when a shortage occurs, the product can be backordered, thus satisfying the demand at a later date. Lost sales models assume that when a shortage occurs, the demand for the units short is permanently lost.

The optimal lot size is again the one that minimizes total costs. In this case, order costs and carrying costs again exist. However, there are now additional carrying costs associated with the buffer stock. The costs of backordering parts or lost sales also result when shortages occur during any inventory cycle.

Most models presented in the literature derive solutions corresponding to situations where the lead time demand is known to vary in accordance with normal or Poisson distributions. Product demand in practice rarely varies in accordance with these types of distributions. Discrete probability distributions are therefore recommended for these types of inventory situations. Readers desiring more information on this type of inventory model should consult the references that appear at the end of this section.

Constant Demand, Variable Lead Time Models

This model addresses the situation exactly opposite of that in the preceding section. Figure 9.2.10 again applies, though with the following changes. The demand is now constant at r units per day. The lead time now varies in accordance with a known statistical distribution. The demand that occurs during the lead time still must be determined. The concepts of buffer stock, backorder costs, and costs of lost sales still apply, as does the concept of service levels. Again, discrete probability distributions are recommended for use in describing lead time variation. A model accommodating discrete probability distributions has been presented by Riggs [21]. This model has been significantly refined by Lee, Malstrom, Vardeman, and Petersen [22] to address true average inventory levels when stockouts occur. Readers desiring more information on this type of model should consult these references.

Variable Demand, Variable Lead Time Models

This family of models imposes the fewest restrictive analysis assumptions, but is also the most complicated set of inventory models. In this analysis situation, both the demand during the lead time and the lead time itself are allowed to vary. The concepts introduced in the preceding two sections again apply. The problem now becomes one of constructing a joint probability distribution in terms of both demand and lead time. This joint distribution will describe the lead time demand. Discrete probability distributions to describe both demand and lead time variation are again recommended.

Reorder Point Model References

Many of the models described in this section have been excerpted from Buffa and Miller [23]. However, there are a variety of newer texts that also describe these models in greater detail. Interested readers desiring more information on this subject should consult Refs. 1, 2, 4, 6, 7, 12, 20, and 24.

JUST-IN-TIME INVENTORY SYSTEMS

Just-in-time (JIT) *inventory systems* are known by a variety of names and terms. These include *material as needed* (MAN), *minimum inventory production systems* (MIPS), *stockless production, continuous flow manufacturing, kanban,* and others. JIT has as its goal the elimination of waste. *Waste* is generally defined as anything other that the absolute minimum resources of material, machines, and labor required to add value to the product being produced.

JIT Benefits

In most cases, JIT results in significant reductions of all forms of inventory. Such forms include inventories of purchased parts, subassemblies, work-in-process (WIP), and finished goods. Such inventory reductions are accomplished through improved methods of not only purchasing, but also scheduling production.

JIT requires significant modifications to traditional methods by which parts are procured. Preferred suppliers are selected for each part to be procured. Special purchase arrangements are contractually structured to provide for small orders. These orders are delivered at exact times as required by the user's production schedule and in quantities small enough to be used in very short time periods.

Daily and weekly deliveries of purchased parts are not uncommon in JIT systems. Vendors contractually agree to deliver parts that conform to preagreed quality levels, thereby eliminating the need for the purchaser to inspect incoming parts. The arrival time of such deliveries is extremely important. If they arrive too early, the purchaser must carry additional inventory. If they arrive too late, parts shortages occur that can stop scheduled production.

Purchasers of such parts often pay increased unit costs to have parts delivered in this manner. While the one-shot costs of structuring the purchase agreement can be significant, the follow-up costs of procuring individual lots of parts each day or week can be reduced to near zero levels. Not having to inspect incoming parts can result in increased product quality and reduced inspection costs on the part of the purchaser.

Fabricated parts are scheduled for production so as to minimize work-in-process (WIP) inventory and stockpiles of finished goods. The JIT philosophy forces manufacturers to solve production bottlenecks and design problems that were previously overcome by maintaining reserve inventory levels.

A number of organizations have successfully implemented JIT procedures that have resulted in significant cost savings. Readers desiring a more detailed overview of JIT policies, procedures, and benefits should consult Refs. 13, 25 to 28, and 31.

Cost-Effectiveness of JIT Systems

The preceding benefits are realized after some significant investments of effort associated with JIT implementation. The cost of structuring blanket purchase arrangements with a variety of preferred suppliers can be significant. Large costs may also be associated with sophisticated tool design procedures to reduce setup costs for producing different products to near zero levels.

Such reductions are absolutely necessary if a lot-for-lot (LFL) order policy is to be applied as described in the preceding section on MRP. Setup costs must be reduced to at least $\frac{1}{100}$ of the corresponding carrying costs for the part being produced [13,16]. If this reduction is not possible, the setup costs associated with an LFL-like order policy may be significant enough to negate the benefits associated with JIT policies [7,13,16].

Software to assess the cost-effectiveness of JIT has been developed by Burney and Malstrom [17,18]. Written in the C language, the software utilizes long sequences of pop-up screens. The screens contain sequences of tutorials that step the user through a detailed cost assessment procedure, which begins by helping the user compile a detailed estimate of costs associated with the inventory system currently in use. JIT implementation costs are next estimated. Costs of blanket purchase agreements, setup reduction, personnel training, and lot sizing are all separately estimated. The user is also guided in estimating the costs of facilities modifications required by JIT.

JIT benefits are next assessed. The net change in inventory costs is estimated. The user is guided in ways to quantify the cost savings associated with better product quality and improved customer delivery. Readers desiring a more detailed description of the developed software should consult Refs. 17 and 18.

SCHEDULING

This section addresses two different types of scheduling. At the macrolevel, master schedules (previously described) must consider both the capacity of the plant and its individual work cells. The master schedule must be continuously adjusted to match per-period workloads with the capacities of machines, facilities, and available personnel. This goal is accomplished through the process of capacity planning.

At the microlevel, the scheduling problem becomes one of determining a priority sequence for competing jobs or orders awaiting processing by a single machine or group of production facilities. The following subsections address these topics.

Capacity Planning

Capacity planning is a method by which the master schedule is adjusted to balance the due dates of jobs or orders against the capacity of the plant and its individual work cells and facilities. This concept is perhaps best illustrated by example. Consider a hypothetical work center with one machine staffed by one worker. Let us suppose that a one-shift operation applies. Consider the 10-week production schedule shown in Fig. 9.2.11. For simplicity, assume that each part requires one hour of processing time on the machine.

From Fig. 9.2.11, it is apparent that there is not enough work to fully occupy the machine and its worker during weeks 20, 21, 28, and 29. The demand in weeks 23, 24, 27, and 28 can be satisfied with the use of overtime. The demand in weeks 25 and 26 cannot be satisfied even if the worker completes six 12-hour days (a total of 72 hours).

The workload may be smoothed by adjusting the schedule as shown in Fig. 9.2.12. Suppose 25 units each from weeks 25 and 26 are moved to weeks 20 and 21. The result is shown in Fig. 9.2.12. The schedule for weeks 20 through 27 inclusive may now be satisfied with the use of 10 hours per week of overtime. While no full workload exists for weeks 28 and 29, it is likely that additional orders will arrive in the next several weeks to fully utilize the production facility during these time periods.

In periods of work underload, the capacity planning procedure seeks to move orders back in time to match workload levels with existing capacities. In periods of work overload, orders are moved forward in time to reduce workload levels. When such schedule adjustments are not possible, it is necessary to hire additional people, add shifts, or lay off personnel. All three situations are undesirable because of the extra costs that are incurred.

Week	21	22	23	24	25	26	27	28	29	30
Demand	25	25	50	50	75	75	50	50	25	25

FIGURE 9.2.11 Sample production schedule.

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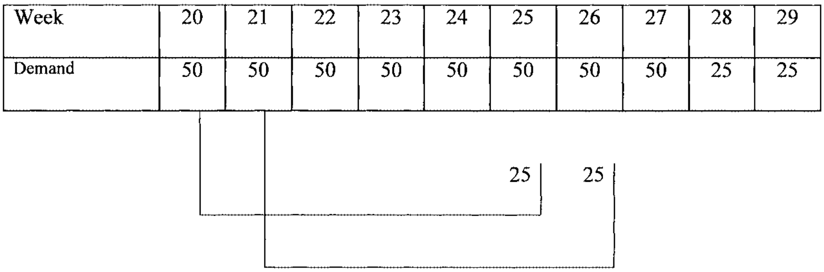

Week	20	21	22	23	24	25	26	27	28	29
Demand	50	50	50	50	50	50	50	50	25	25

FIGURE 9.2.12 Schedule changes to smooth production.

Vollman, Whybark, and Berry [1] have described three separate types of capacity planning methods. The methods differ in the amount of production data used to afford increasing levels of detail in assessing workload levels. These methods are described in the following subsections.

Capacity Planning Using Overall Factors. Capacity planning using overall factors (CPOF) is a relatively simple approach that results in a "rough-cut" capacity plan. The inputs come from the master schedule rather than from the MRP tables associated with individual parts in the bill of materials. Workload levels are derived from performance standards or historical data for end products only. Fabrication times for components included in the end item are embedded in these totals. This data is used to derive workload levels. The CPOF method does not consider the time shift associated with the lead times for all component parts in the end item.

Capacity Bills. This method provides a more direct linkage between different end products being produced and the respective capacities required by these different end items in various work centers. The method is responsive to changes in product mix of the end items produced. Additional data is required to use this approach. Lot sizes for each end product and their respective components must be known. Setup and run times for each lot must be defined for each work center in which processing is required.

Resource Profiles. This approach further refines the capacity bills procedure. It considers the lead-time requirements associated with each node in the parts explosion diagram. All data for the previous method is used, but is defined to occur in the specific period during which the work on a specific part or subassembly is scheduled to take place. This method is the most detailed (computationally robust) of the three approaches that have been described.

More detailed information on each of these three capacity planning methods may be found in Ref. 1. The descriptions of each method are illustrated with detailed numerical examples.

Machine Scheduling Methods

A variety of methods exist for the scheduling of jobs or orders within a given work cell. For most rules, a notation of the form $n/m/C$, applies. In this notation, n denotes the number of jobs or orders that are to be scheduled, m refers to the number of machines within the work cell, and C refers to the objective or criterion addressed by the developed schedule.

Common scheduling objectives are to deliver or complete the orders by the due dates required by the customer. This is accomplished by minimizing the average or maximum lateness for a sequence of jobs or orders. Another common objective is to minimize the elapsed time that the order or job is in process within the work cell. This is equivalent to minimizing the average or maximum flow time for a sequence of jobs.

Extremely complex math is involved in proving that job sequences derived from specific rules satisfy specific scheduling criteria. Most early work in analyzing scheduling methodologies therefore focused on work cells consisting of only one or two machines. A review of this early work follows.

Shortest Processing Time Rule. The shortest processing time (SPT) rule schedules jobs across a machine or set of production facilities in order of increasing processing times. For n jobs that are sequenced across a single machine, it may be proved that the SPT rule minimizes the mean flow time for all jobs. *Flow time* refers to the sum of the time the job spends in queue plus its processing time.

The primary disadvantage of the SPT rule is that jobs with long processing times usually are delayed in reaching the front of the queue. They are therefore often completed long after the due date required by the production schedule. This problem is addressed by using a truncated form of the SPT rule that forces jobs with long processing times to the front of the queue after they have awaited processing a specified length of time.

Due Date Rule. The due date (DDATE) rule sequences jobs across a machine or set of production facilities in ascending order of date by which the order or job is due to be completed. Those jobs with the earliest due dates are worked on first. For n jobs and one machine, it may be proved that the DDATE rule minimizes the maximum lateness for the sequence of jobs that are scheduled.

Slack Time Rule. The slack time (SLACK) rule sequences jobs across a machine or set of production facilities in order of increasing slack time. *Slack time* is the difference between a job's due date and its processing time. For any job i in a sequence of n jobs, the slack time is defined by Eq. (9.2.13).

$$t_i = d_i - p_i \tag{9.2.13}$$

where t_i = slack time for job i
d_i = due date for job i
p_i = processing time for job i

With the slack time rule, jobs with minimal slack have the greatest risk of being late. They therefore are placed first in the scheduling sequence. For n jobs and one machine, it may be proved that the slack time rule maximizes the minimum lateness for the sequence of jobs or orders that are scheduled.

Multiple Machine Rules. Most scheduling applications involve the use of more than one machine. Conway, Maxwell, and Miller [29] overview two methods that address $n/2$ and $2/m$ scheduling problems. Johnson's algorithm is applicable for $n/2$ scheduling problems. Application of this procedure will yield a sequence that will minimize the maximum flow time of all n jobs across the two machines.

The authors also illustrate a graphical scheduling procedure for a $2/m$ scheduling problem. The goal again is to minimize the maximum flow time for the two jobs across the set of machines. Times at which both jobs will need a given machine are depicted on a two-dimensional graph as conflict areas. Scheduling paths are illustrated that pass around these regions, and attempt to maximize the amount of time that both jobs receive simultaneous processing.

Readers desiring more information on either of these methods should consult either Conway, Maxwell, and Miller [29] or Baker [30].

First-Come, First-Served and Random Scheduling. These two methods are equivalent to doing no scheduling at all. In the first-come, first-served (FCFS) method, jobs are processed in the order in which they arrive at the machine or facility. With the random method, a completely arbitrary job sequence is randomly selected. The value of these methods comes from comparing them to other scheduling rules and heuristics. The FCFS and random rules serve as

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comparison benchmarks to show how much improvement can be obtained through use of other scheduling methodologies.

The RAND Simulation Studies. The RAND simulations were performed in the 1960s by the RAND Corporation. They have been described in detail by Conway, Maxwell, and Miller [29]. These studies are historically significant. They are one of the first large-scale digital simulation analyses that analyzed a variety of scheduling rules in a multiple-machine environment.

Much of the RAND evaluation focused on an $n/9$ scheduling environment. A variety of evaluation criteria were defined, including average number of jobs in queue, work-hours remaining, work-hours completed, average flow time, average job tardiness, and fraction of jobs tardy.

Job due dates were generated in four different ways. These included a constant multiple of the job's processing time, a date proportional to the number of operations in the job, a constant due date for all jobs, and due dates that were randomly assigned.

A variety of scheduling rules were analyzed including SPT, DDATE, SLACK, random, and FCFS. Additional rules included those based on the amount of work in queue, the amount of work remaining, the number of job operations remaining, and those that prorated both due dates and slack time between a job's operations.

The SPT rule was consistently among the best performers for all evaluation criteria. SPT-scheduled jobs were found to have the smallest average flow times. The SPT rule also performed best in terms of average tardiness and the number of jobs tardy.

The results of the RAND simulations have been confirmed in a number of subsequent simulation analyses. Because of the excessive lateness of SPT sequence jobs with large processing times, a truncated version of the SPT rule is generally recommended for use. Readers desiring additional information on the RAND simulations and scheduling rules in general should consult Refs. 29 and 30.

SUMMARY

This chapter has sought to overview a number of principles and techniques of production planning and inventory control. Several books have been written about many of the major topics that have been addressed, and the reader may refer to them for more in-depth coverage.

Where appropriate, numerical examples and mathematical notation have been used to illustrate concepts and procedures. None of the sections in this chapter is intended to provide stand-alone coverage on any topic. References cited throughout the chapter (see reference section that follows) provide sources containing additional information on each major subject, and readers are urged to consult these references.

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CHAPTER 9.3

SUPPORTING LEAN FLOW PRODUCTION STRATEGIES

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As the manufacturing systems and strategies change, the catalyst for change—industrial engineering—also has to change. But by how much? This article will address traditional industrial engineering technologies in traditional manufacturing environments and the resulting problems, the lean flow production strategy and anticipated benefits, and an approach for refitting industrial engineering technology into a lean flow production environment.

INTRODUCTION

Balancing customer and shareholder satisfaction should be the ultimate goal of any business strategy, in addition to making money. Understanding the factors that are important for company growth is essential. Improvements in machine utilization and efficiencies of operations, and reductions in direct labor are no longer getting the total job done. Industrial engineers need to reassess these indices and add others with a focus on improving the entire system versus the work of individuals or small groups.

Work gets done through people. People are responsible for process operations, flow of materials, and quality output. People will also respond to enlightened direction—that is, commonsense direction in terms they can understand. They understand the constraints that prevent them from doing their jobs. They understand actions that make their jobs better. Keeping their machines maintained, supplying proper tools, supplying the right material of proper quality on time, providing necessary training, and establishing achievable fair goals are all means to make improvements they can understand. These are issues that interrupt the flow of quality products at a competitive product cost and at a delivery rate that matches customer demand. Companies should focus on these issues for optimum performance of the entire organization. Owners of the process are key to this objective, as it is through them that improvements are made. Industrial engineers have to connect philosophically with the people doing the work. They have to reassess some of the traditional approaches that were often viewed as adversarial in nature and were not well received or accepted.

This does not mean industrial engineers have to abandon their stopwatches or predetermined motion time systems, or give up flowcharting, human-machine charting, or methods improvement analysis. Industrial engineers do not have to give up plant layout or capital equipment justification. However, they do have to change the manner and focus in which they use these tools. The focus has to be on the entire system of converting raw material into finished goods. Operations and processes can no longer be analyzed in isolation. Focusing on the improvement of value-added activities only serves to put blinders on areas where the greatest gains in productivity can be made. Industrial engineers must not succumb to pressures of unenlightened direction but should rather be proactive in taking steps to foster making manufacturing a strategic advantage for the company. For purposes of restricting the scope of this chapter, only the manufacturing portion of the entire organization is considered.

Importance of Strategies

Business strategies attempt to set a company apart from others. Business strategies of the past included technology, materials requirement planning, manufacturing resource planning (MRP), statistical process control, quality, just-in-time (JIT), and others. Without debating the merits of each, the fact is that the nature of manufacturing organizations has been evolving rapidly. Traditional strategies have failed to be effective in keeping up with this evolution. Breaking from tradition is required to meet customer expectations and maintain a long-lasting competitive position.

Strategies are important because they set much of the direction of the company. A strategy that offers companies many advantages over their competition is one that focuses on reducing response time to customer demand. This strategy is based on customer demand driving the production flow. In this chapter, that strategy will be referred to as *lean flow production.* Competitive advantage is improved on several fronts: speed to market, cost, and quality. The strategy promotes reduced cycle time, reduced working capital, and flexible manufacturing organizations.

LEAN FLOW PRODUCTION

Response Time

Lean flow production is a comprehensive business strategy that links manufacturing processes together and synchronizes them to daily customer orders. Lean flow production includes methodology from other techniques such as lean manufacturing, JIT, time-based manufacturing, Demand Flow® technology, the Toyota production system, the visual factory, flexible manufacturing, total quality management (TQM), synchronous manufacturing, and work cells and work teams. Within the manufacturing organization, this strategy focuses on a reduction in response time. *Response time* is the time it takes from receiving an order to delivering that order.

Determining current product response time requires some research. Look at route sheets, release dates and ship dates, MRP data, production schedules, or anything else that will supply data about when orders were received and actually shipped. Plot the data by product family to identify variations. Plot the average promised or quoted lead time and compare it with actual response time. Orders were probably shipped early as often as they were shipped late.

In Fig. 9.3.1, historical data from four product families are plotted. In this company, marketing quotes a 14-day delivery for all product families. Notice that only 20 percent (8 of 40) of the orders were delivered in 14 days or less. Now, assume that all customers wanted the product in 14 days exactly—no sooner, no later. This assumption is valid in today's market. Many companies have already completed the evolution to lean flow production internally and are now extending these concepts back to their suppliers.

In the example in Fig. 9.3.1, only 1 order was delivered exactly on time. This indicates, among other things, a possible disconnect between marketing and manufacturing. Manufacturing may not understand the processes well enough. Marketing may not understand the effect product mix has on manufacturing. In lean flow production, manufacturing processes have to be understood better than ever thought possible—better than ever before.

SUPPORTING LEAN FLOW PRODUCTION STRATEGIES

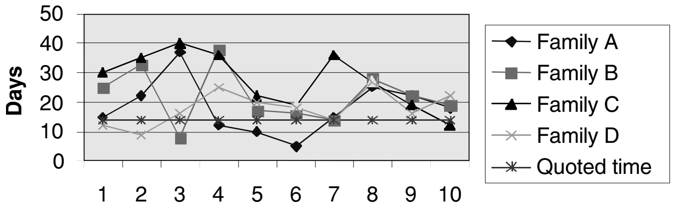

FIGURE 9.3.1 Response time by product family (typical in traditional production).

In traditional manufacturing, response time is expanded or lengthened just by the nature of the way companies have self-imposed arbitrary policies and practices. Manufacturing is typically broken down into departments that each have a schedule, a queue, and work steps to proceed through; then the items are moved into storage prior to going to the next department on the routing cycle, as depicted in Fig. 9.3.2.

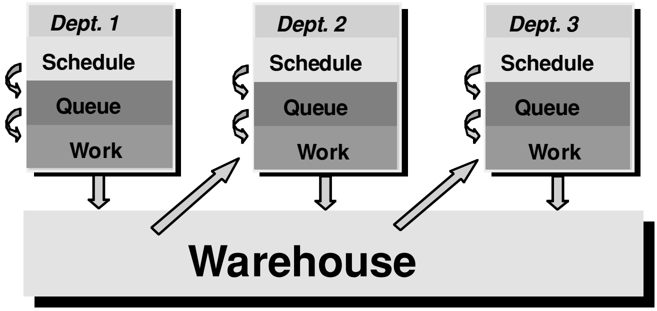

FIGURE 9.3.2 Traditional response cycle.

Response times are unnecessarily extended as a result of this approach. The amount of time actually adding value to the product is a small percentage of the total time. Consider a lot size of 100 units progressing as one lot through the various assembly processes. When 1 unit is having value added to it, the other 99 are waiting for their turn. This equates to 99 percent of the time a product is on the shop floor taking up space and no value is being added to it. Product stored on a shelf, on a bench, or even on a conveyor are waiting. No value is being added while products wait for their lot mates to be completed. Products in a traditional environment spend more time waiting than adding value and progressing toward its customer. Figure 9.3.3 demonstrates this phenomenon.

Typically the total response time in a traditional environment will equal the number of levels of the indentured bill of material (BOM) multiplied by the manufacturing lead time.

$$(\text{Levels of BOM}) \times (\text{manufacturing lead time}) = \text{total response time traditional}$$

If, for example, the BOM had 4 levels and a 2-week lead time for each level, the response time would be 8 weeks.

$$4 \text{ levels of BOM} \times 2 \text{ weeks} = 8 \text{ weeks response time}$$

In lean flow production, the BOM is considered only as a pile of parts. The BOM is flattened, ideally to only one level. This allows industrial engineers to determine the best position in the process to assemble a part.

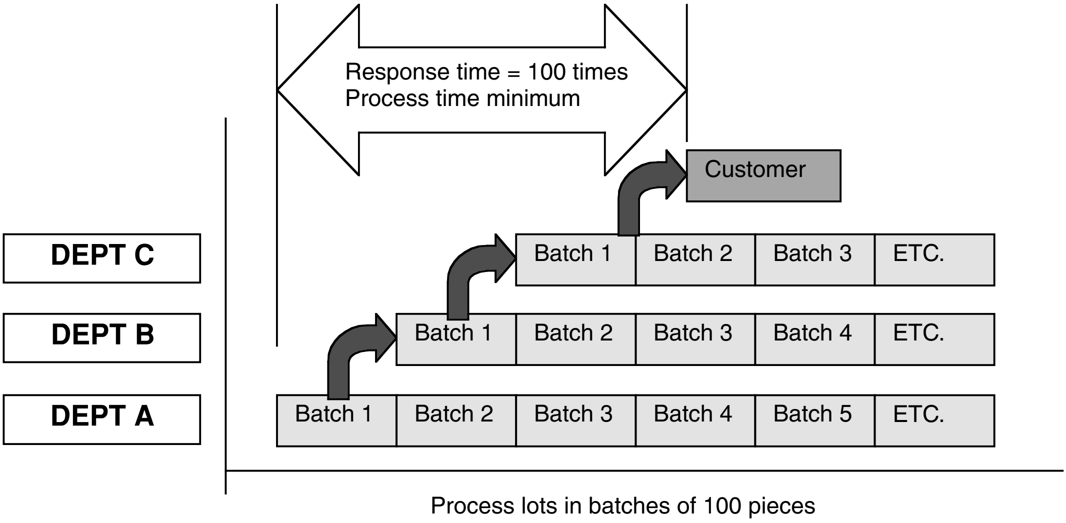

FIGURE 9.3.3 Traditional response time.

Inventory Turns

Inventory turns are an indication of how much material and therefore how much working capital is invested in the system. The higher the turns, the better. A rough estimate of minimum inventory turns in this example would be

$$12 \text{ months/response time in months} = \text{inventory turns}$$

$$12 \text{ months/2 months (8 weeks)} = 6 \text{ inventory turns}$$

What would happen to response time when the manufacturing processes are linked and then synchronized to daily customer orders? Figure 9.3.4 shows the impact to response time by just connecting processes and continually adding value to the product. Product no longer has to wait on its lot mates before proceeding to the next value-added process. Waiting time adds no value yet increases response time.

Lean flow production focuses on response time reduction. Response time reduction positions a company's manufacturing operations to a competitive advantage that will grow the business. Processes are linked on the factory floor, reducing inventory and reducing or eliminating waiting time. Companies are significantly impacted financially because reductions in inventory free up a company's working capital. Industrial engineers can take a leadership role in applying commonsense engineering technology to make companies more competitive.

Product response time is only one in a series of steps required in developing a flow line. The following sections introduce the steps and tools required in engineering a successful flow line.

INDUSTRIAL ENGINEERING FOR LEAN FLOW PRODUCTION

Industrial engineering, when properly directed or enabled to exercise initiative, is a catalyst for making improvements in manufacturing operations. Unfortunately, the direction or initiative traditionally has been targeting a reduction in direct labor, out of context with improvements in the entire system.

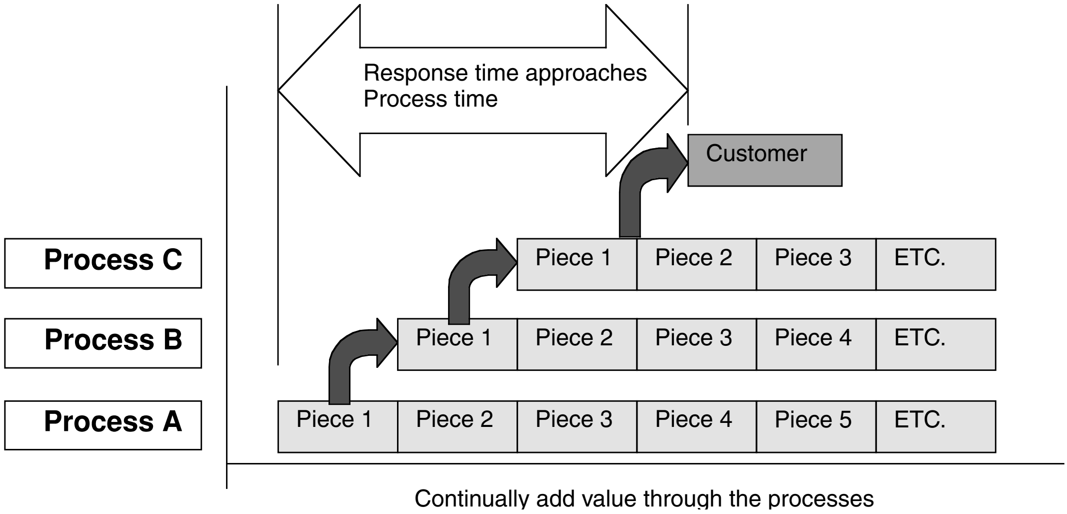
Response time approaches
Process time
Customer
Process C
Process B
Process A
Piece 1
Piece 2
Piece 3
ETC.
Piece 1
Piece 2
Piece 3
Piece 4
ETC.
Piece 1
Piece 2
Piece 3
Piece 4
Piece 5
ETC.
Continually add value through the processes

FIGURE 9.3.4 Synchronized response time.

Cost reduction programs seldom look at all costs of doing business. There are too many walls and compartmentalized functions that are off-limits. Direct labor costs are a small part of the total cost. Total elimination of direct labor costs, in many cases, is not significant enough to achieve competitive position with regard to price. Now the industrial engineer's goal is to focus on the entire system and its effectiveness at increasing throughput while reducing inventory and operating expenses.

In a lean flow production environment the industrial engineer has to understand and use the following tools to achieve maximum effectiveness of manufacturing organizations.

- Product pace time
- Process sequence map
- Operational sequence sheets
- Total product response time
- Total product time
- Resource requirements (equipment and human)
- Workstation definition
- Initial layout

Product Pace Time

If one were to plot actual deliveries over time, many if not most, manufacturers' charts would resemble a hockey stick. The *hockey stick curve* is given its name because of its shape. There are no or few deliveries early in the period, then a flush of product at the end. Lean flow production environments are designed to have a continuous flow of completed quality products at a rate matching customer demands. That demand rate is the basis for the product pace time. Product pace time (P pace) is the rhythm at which a process must run to fulfill the daily demand. In determining pace time, engineers will determine the effective work hours per day and the daily maximum rate the line must produce. The maximum daily production rate (P max) is acquired directly from marketing since they have the closest relationship with customers. For this reason marketing must be made part of the process.

Effective work hours per day (W) varies from company to company due to differing policies for shift length, lunches, breaks, and other allowances that take away from available work hours. A typical scenario is an 8-hour shift with a half-hour lunch and two 10-min breaks.

$$\begin{aligned} W &= 480 \text{ mins} - 30\text{-min lunch} - 2\ (10\text{-min breaks}) \\ &= 430 \text{ mins } (7.17 \text{ effective work hours per day}) \end{aligned}$$

The product pace time expressed mathematically is

$$P \text{ pace} = W/P \text{ max}$$

$$W = \text{effective work hours per day}$$

$$P \text{ max} = \text{designed daily maximum rate}$$

For example, if marketing requires 23,000 units during a 20-working-day month, and manufacturing is designed to run two 8-hour shifts each having a half-hour lunch/dinner, plus two 10-min breaks per shift, the resulting P pace would be

$$P \text{ pace} = W/P \text{ max}$$

$$W = (480 \times 2) - [(30 \times 2) + (10 \times 4)] = 960 - [60 + 40] = 860 \text{ min}$$

$$P \text{ max} = 23{,}000/20 = 1150 \text{ units per day}$$

$$P \text{ pace} = 860/1150 = .75 \text{ min}$$

This would mean that to satisfy the demand a completed product would need to come off the end of the line every .75 min.

Process Sequence Map

Like the traditional industrial engineering process flowchart and indentured manufacturing routing, the process sequence map defines the relationships of manufacturing processes required to produce a product. Each product is built in stages. The process sequence map defines the stage relationship of all manufacturing processes required to build a product. Figure 9.3.5 shows an example of a process sequence map for producing a flashlight.

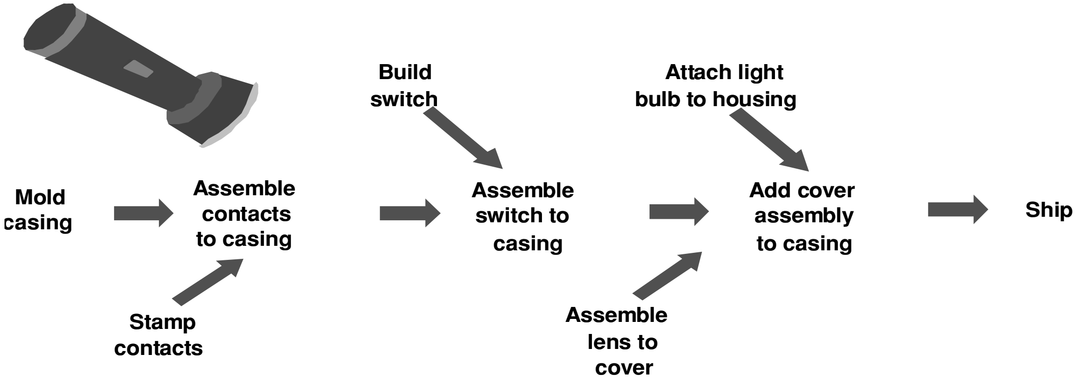
Build switch
Attach light bulb to housing
Mold casing
Assemble contacts to casing
Assemble switch to casing
Add cover assembly to casing
Ship
Stamp contacts
Assemble lens to cover

FIGURE 9.3.5 Process sequence map.

The process sequence map in Fig. 9.3.5 shows that casings are molded, contacts are stamped then assembled to the casing, the switch is built and assembled to the casing, the lens and cover are assembled, the light bulb is assembled to the housing then assembled to the casing, and finally the completed product is shipped.

Operational Sequence Sheets

Operational sequence sheets define the work required and the quality criteria necessary to build a product. All sequential work content, the engineered time required, materials consumed, tools and equipment needed, and the quality actions required are specified on the sheets. The accuracy of this information is most important as it will become the basis for operation definition, line balance break points, line design, and product mix planning. In traditional industrial engineering these are methods sheets or process sheets. Figure 9.3.6 is a typical example of an operational sequence sheet.

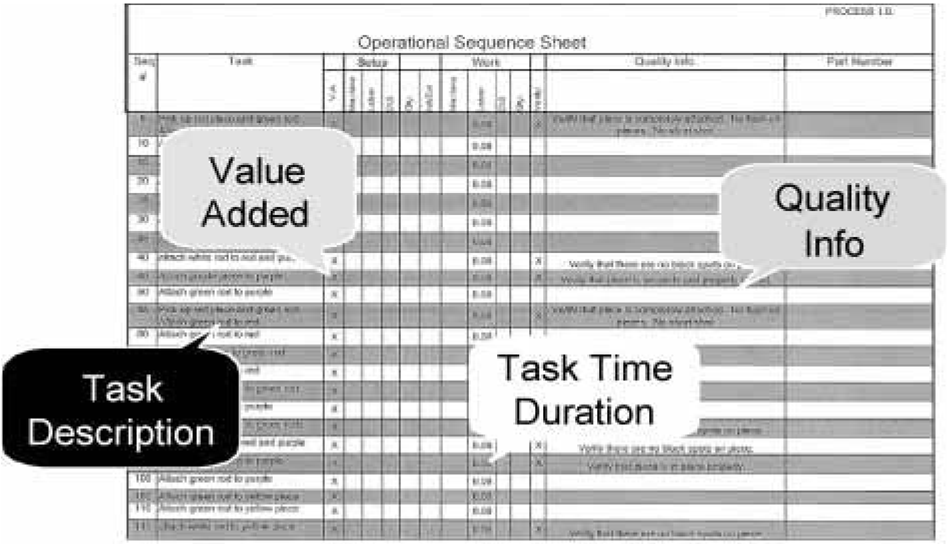

FIGURE 9.3.6 Operational sequence sheet.

Each step in the process, including material handling and inspections are recorded in the task description area. A column is included to identify the task as value-added. The task time duration are times engineered using a recognized industrial engineering work measurement tool. Work measurement systems that use a computerized database that can be easily updated as improvements in methods and processes occur are preferred. This will greatly enhance the accuracy of initial manufacturing line design and aid in redesign of the line as demand fluctuates. Critical quality information and criteria for each task is documented. It is also important to document materials consumed and tools or equipment needed for each task.

Total Product Response Time

How long does it take from the start of the first process to complete the first good product? This measurement is total product response time. Total product response time is the longest calculated time path in the manufacturing process, measured from the end of the process through each path. Adding engineered times to each of the sequences of a process sequence map as in Fig. 9.3.7, the total product response time is 12.8 min.

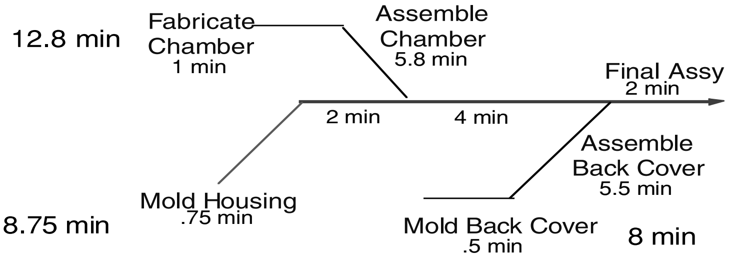

FIGURE 9.3.7 Total product response time map.

The 12.8 min is the sum of the assembly time starting at the end of the process working back. In this example total product response time would equal 2 min for final assembly, plus 4 min to assemble chamber to housing, plus 5.8 min to assemble chamber, plus 1 min to fabricate chamber. This would be the minimum amount of time required from the time of initial process through completion.

Total Product Time

Total product time is the sum of all the time required to build the entire product. This can be the sum of the sequences on the operational sequence sheets, or the sum of all times on the total product response time map. Again, these are engineered times using proper industrial engineering work measurement tools. In the example in Fig. 9.3.7 the total product time is 21.55 min. The calculation equals 2 min + 5.5 min + .5 min + 4 min + 2 min + 5.8 min + .75 min + 1 min, which equals 21.55 min.

Resource Requirements

Industrial engineers have traditionally been asked to determine staffing requirements and equipment resources needed by manufacturing. In lean flow production, industrial engineers still determine the number of workstations and other resources needed to meet customer requirements. The number of resources required equals the total product time divided by the calculated pace time. For example, if total time to build is 12 min and pace time is 1.5 min then

$$\# \text{ resources} = \text{total product time/pace time} = 12/1.5 = 8 \text{ resources}$$

The number of resources is then broken into resource requirements. Partial resources should be rounded up. For example, 1.1 becomes 2.

Workstation Definition

This is where the operational sequence sheets play an important role. To enhance the manufacturing line's ability to obtain maximum value-added time, simply add the time for each sequence until they total the calculated pace time. (This identifies the break points for work to be accomplished at each workstation.) Then repeat the process. The number of break points

SUPPORTING LEAN FLOW PRODUCTION STRATEGIES

should equal the calculated number of resources required. This is a draft cut at line balancing, another traditional industrial engineering function. An example is shown in Fig. 9.3.8.

Once the value-added tasks are defined for each workstation, assurances are needed that the workstation size will accommodate the materials, tools, and equipment required.

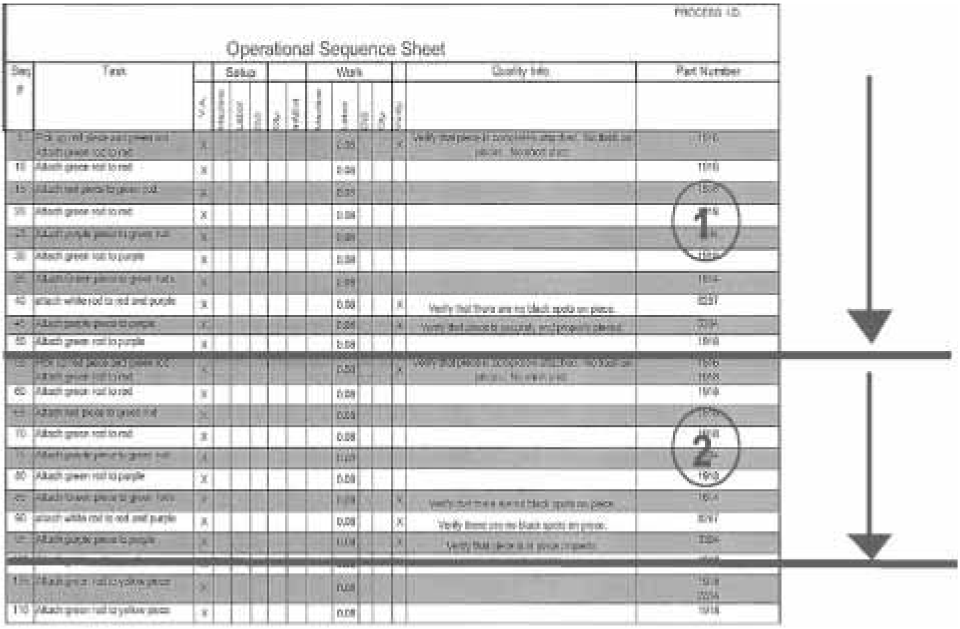
PROCESS I.D.
Operational Sequence Sheet
Seq #
Task
Setup
Work
Quality Info
Part Number
1
2

FIGURE 9.3.8 Workstation definition.

Initial Layout

Keep the initial line layout simple. The initial line layout should look similar to the total product response time map with the number of resources required. The line may include a main assembly line and feeder lines for subassemblies. Figure 9.3.9 is an example of an initial line layout requiring 11 resources. This type of flow arrangement is ideal in a factory.

Performing these eight steps will result in a synchronized flow of product in precise cadence with your customer demand.

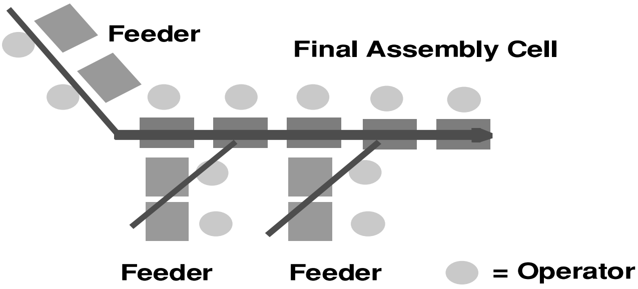
Feeder
Final Assembly Cell
Feeder
Feeder
= Operator

FIGURE 9.3.9 Initial line layout.

INDUSTRIAL ENGINEERING FOR INVENTORY REDUCTION

Inventory Reduction

Industrial engineers have traditionally not been involved in inventory management, other than to design and install storage systems or material-handling systems. Projects ranged from placing additional shelves in a work center to major installations of automatic storage and retrieval systems. Industrial engineers were traditionally asked to solve problems with limited scope. Benefits were isolated to work centers or departments but were of little or no help to the entire system's ability to satisfy the demands of the customer. Material handling adds no value to the product. As mentioned earlier, when considering industrial engineering projects it seems absurd to spend time and money to make a non-value-added activity more efficient. In the same vein, excess inventory consumes space and money and does not help the system's performance, so why spend time and money creating space and systems to handle this excess? Industrial engineers may have unknowingly aided the delay of companies moving in the right direction—toward lean flow production strategies.

Zero working capital is a goal of lean flow production strategies. This is consistent with the ultimate goal of satisfying customers and owners. With zero working capital all material is consumed within a very short time frame (ideally, the total product response time). This results in very little inventory on hand, as either finished goods or in process. Inventory takes up space. Space costs money. Storage space takes away from available value-added space. If storage space is needed, someone is required to store items. Stored items need to be found and retrieved when needed. Advanced notification of needs is required to allow time to find everything. In an effort to reduce search time, material for many units or a batch is pulled as opposed to pulling only enough for the *one* the customer will buy today. This is called *kitting.* Kits are released to a kit-release schedule. None of this adds value to the product, but does add cost. This is the nature of scheduled-based manufacturing. Lean flow production considers non-value-added activities as waste and targets for elimination, thus increasing the ratio of value-added to non-value-added activities.

Stockrooms grow and consume space that could be used for value-added activities. The material purchased to build to the anticipated demand for a product mix consumes dollars and space to such a degree that a materials manager needs to be hired. Product produced with no customer becomes finished goods inventory requiring more storage space. In a scheduled manufacturing environment, also known as a *batch-push environment,* terms such as economic lot sizes, incoming inspection, stocking, kitting, de-kitting, indentured bill of materials, routings, work centers, departments, and manufacturing lead times are used in describing the system. Virtually all of these elements are deterrents to advancing a product closer to a customer, and should be eliminated.

Point of Consumption Material Delivery

The only reason material is needed is to build a product. The operator adding value to a product does not care where the material comes from, only that it is there when it is needed and that it is of acceptable quality. Why not, then, arrange to have quality material delivered directly to the person responsible for adding value to it or consuming it? Receiving, incoming inspection, stocking, kitting, de-kitting, and all the support mechanisms associated with all of these non-value-added tasks would be eliminated. Depending on the size and value of the material, consider having only what can be consumed within a reasonable amount of time delivered to the point-of-use (POU). Weekly, daily, or even hourly deliveries can be arranged with many suppliers today. Some suppliers will even maintain ownership of the inventory until the material has been consumed or delivered in a completed product. This is possible because total product response times are so short. In many cases, suppliers actually get paid sooner under this arrangement as opposed to being paid to deliver in larger batches to a stockroom. Remember that zero working capital is good, and is a goal of lean flow production strategies. If the nature or cost of the material make POU deliveries by suppliers impractical, an alternative option is to establish a small raw and in-process storage areas close to the POU operations. Figure 9.3.10 graphically shows that as a rule up to 7 days' inventory would be stored in this raw and in-process buffer area. No more than 1 to 3 days of inventory would be stored at the workstation (POU). Fourteen to 28 days of inventory in a stockroom should be more than adequate.

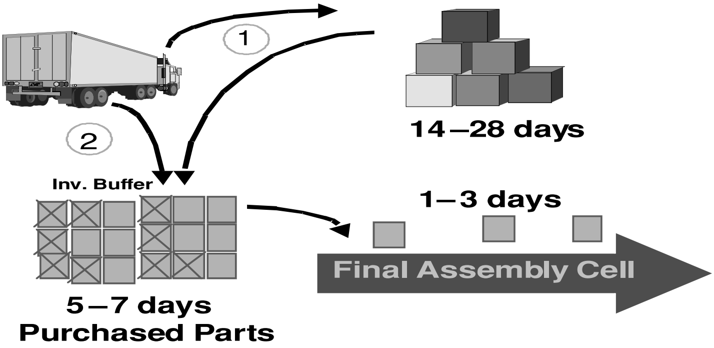

FIGURE 9.3.10 Inventory requirements in days.

Do not allow suppliers to deliver any material before it is needed. If they own it until it leaves in a completed product, this will not be as much of a problem. Products cannot be shipped with missing parts. All the material is needed. Not having the right parts in the right quantity stops a product from progressing closer to being sold. Focus on achieving material receipts that match customer demand. Establish a signaling system that works to inform suppliers when to deliver.

LINKING PROCESSES USING PULL SYSTEMS—KANBANS

Lean flow production is a comprehensive business strategy that links manufacturing processes together and synchronizes them to daily customer orders. Links are established at each step of the process as well as each path of material supply using systems that are designed to pull production and materials through the process.

Two different types of pull mechanisms or kanbans designed to pull product or material through the process are presented in Fig. 9.3.11. The Through kanban is used to pull work through workstations and to balance operations. The One for One kanban is used to pull work from buffers or dedicated resources. There are many other types of kanbans that can be used, however, they will not be covered in this chapter. The size of each of these kanbans is engineered using data related to the real-world dynamics of the nature of the business. Industrial engineers should be equipped technically to calculate each of these kanbans.

Calculating the Through kanban (Kt) size, which is used to pull product through a workstation or to balance operations is achieved by the following formula:

$$Kt = \frac{C(At - P_{pace})}{P_{pace}} \quad C = \frac{H}{At}$$

where C = the number of cycles per day
H = the number of effective working hours per day divided by the actual time of the operation At
At = actual time of the operation
$Ppace$ = product pace time, the rhythm at which a process must run to fulfill the daily demand

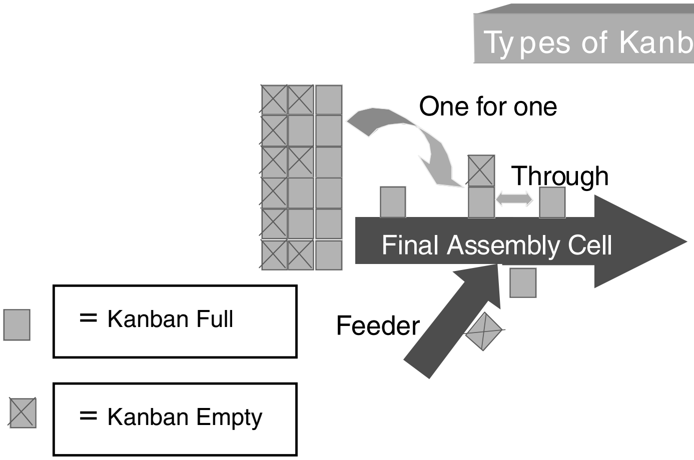

FIGURE 9.3.11 Linking processes using pull systems.

If the effective working hours per day were 7.3, the Ppace is 20 min, and the actual time of this process is 29 min, the Kt would be calculated as follows:

$$C = \frac{(7.3)(60)}{29} = 15.1$$

$$Kt = \frac{(15.1)(29 - 20)}{20} = 6.8 \text{ or } 7 \text{ units}$$

This means that 7 units will be required in a kanban at that station at the beginning of the shift, and the kanban will be empty at the end of the shift. Seven more units will have to be produced during an off shift to replenish this Through kanban.

A One for One kanban (Ko) is used to replenish material supplies or to pull product from buffers. This is also known as *single-card replenishment kanban.* This kanban is calculated by using this formula:

$$Ko = \frac{Pm \times Q \times R \times (1 + V)}{H \times P}$$

where Pm = the production maximum
Q = quantity per product
R = replenishment time
V = variation factor that is the allowed overage or shortage percentage
H = hours available to replenish
P = the package quantity

Assuming our production maximum was 2400 units per day and we required 2 of this part per unit. Also assume the factory runs two 8-hour shifts per day and it takes 45 min to replenish the material into the kanban. The parts come in boxes of 200 per box. For this part policy allows a ±20 percent variation in the kanban. Using this formula the kanban size would be calculated as follows:

$$Ko = \frac{2400 \times 2 \times (45/60) \times (1 + .2)}{(8 \times 2)(200)}$$

$$Ko = 1.35 \text{ or } 2 \text{ boxes}$$

This means that 2 boxes of parts are required in the kanban. Kanbans can be used to establish a two-bin system where the number of parts in each bin is sized based on the One for One formula. A signaling scheme can be developed with the suppliers, the simpler the better. Calculate the quantity required per bin. Consume from one bin. When the bin is empty, this is the signal to a supplier to replenish. Send the signal, then begin consuming from the second bin. If calculations are correct, the first bin is now full of parts and has been returned before all the parts in the second bin have been consumed. Done correctly, the operator should never run short of parts. Part shortages are a major constraint on production.

SUMMARY

Common sense and logic are fundamental tools of the industrial engineer's intuition. The fundamental precepts of lean flow production make sense to this intuition. In this environment industrial engineers are free to remove the blinders of unenlightened traditional techniques and broaden the impact of their actions. No longer saddled with reducing direct labor as an end, the industrial engineer is free to improve any and all areas where non-value-added activities occur. The goal is to make improvements to the system that will reduce product response time to market, improve space utilization for value-added activities, reduce inventory levels, reduce setup time, improve work flow through shared resources, achieve 100 percent on-time deliveries, reduce working capital in the system, and improve quality. The fundamental tools, with which to do this, have not changed, only the soundness of their application.

BIOGRAPHY

Ronald Egan has over 25 years of manufacturing experience from the assembly line to the corporate staff. He is a recognized leader in establishing manufacturing infrastructures that are efficient and responsive to the customer as well as the company. Egan holds a master's degree in business administration from New Hampshire College, a bachelor of science in industrial engineering from the University of Massachusetts at Lowell, and a degree in machine design technology from Wentworth Institute of Technology. He is a senior consultant with H. B. Maynard and Company, Inc., where he manages projects that provide productivity solutions to Maynard clients worldwide through the application of industrial engineering products and services.

Source: MAYNARD'S INDUSTRIAL ENGINEERING HANDBOOK

CHAPTER 9.4

JUST-IN-TIME AND KANBAN SCHEDULING

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Scheduling is a very important function in manufacturing systems, since it impacts how well resources are used. For just-in-time (JIT) assembly systems, the scheduling function differs somewhat from what is used in conventional job shops and flow shops. The JIT philosophy (proposed by Toyota Motor Corporation), which uses kanban as an information tool, is particularly suited to mixed-model manufacture of products characterized by large-variety, small-quantity demand such as automobiles, electronics, and telecommunication equipment. Because of the "pull" characteristic of JIT systems, it is the sequence schedule of products on the final assembly line that primarily determines the amount of inventory, as well as the efficiency of workforce utilization within the system. Models and solution methodologies for the sequencing of products for JIT assembly lines are discussed in this chapter.

INTRODUCTION

The just-in-time (JIT) concept is one of the core elements of the famous Toyota production system, and it basically entails the manufacture of the necessary units in the necessary quantities at the necessary times. The realization of JIT production in the entire firm eliminates the need to maintain unnecessary inventories in the factory, and this consequently reduces inventory carrying costs and increases capital turnover ratio. To avoid excessive setup costs, however, an inherent subobjective that is vigorously pursued focuses on developing and incorporating efficient ways of reducing setup time. An important associated method that is implemented alongside JIT is continuous improvement (kaizen), which makes it possible to identify and eliminate all forms of waste in the manufacturing system.

JIT is essentially a pull production system, in which a preceding process produces units to replace the ones already used up by a subsequent process. It differs from the conventional push system whereby a preceding process produces and stocks units for use by a subsequent process, without particularly taking into consideration the needs of that process. Manufacturing systems are generally characterized by cascading levels of production from the final product down to the raw materials; therefore, the pull effected by demand for subassemblies and parts by the assembly line is transmitted by means of an information tool (kanban) through the linked preceding processes at all levels in the system.

JIT MANUFACTURING AND THE KANBAN SYSTEM

Manufacturing is not an end in itself; it is the means of transforming certain input elements to yield products that have value, thereby meeting some needs of society or industry. Manufacturing mostly involves discrete items such as computers, machine tools, cars, telecommunication equipment, and so on. The cost of the product has long been an important factor for manufacturers, and if they are to avoid operating at a loss, they need to cut costs by reducing wastes in every way possible and retain only those operations that add value to the final product. Four kinds of waste associated with manufacturing are outlined as follows.

1. Excessive production resources
2. Overproduction
3. Excessive inventory
4. Unnecessary capital investments

Designing the manufacturing system by considering the preceding elements which link to each other somewhat in succession, is a sure way to reduce costs. This will reduce the price at which the product can be sold, boost its competitiveness, and consequently increase the manufacturer's profits. These principles are a hallmark of the Toyota production system, of which JIT manufacturing is a part.

The Just-in-Time Concept

Production would be unnecessary if there were no demand (or at least anticipated demand) for a product. On one hand, if demand exceeds supply, then there will be a shortage loss for the manufacturer who has enough capacity and yet is unable to meet the demand. On the other hand, if supply far exceeds demand, then warehouse(s) would need to be provided for the products that have not been sold. Apart from this cost, there is also the cost resulting from obsolescence—a high risk caused by the rapid rate of technological innovation.

The just-in-time concept entails producing the necessary units, in the necessary quantities, at the necessary times. The units here apply to the various levels in the multiechelon structure that characterizes most production systems. It is therefore a pull system whereby a preceding process makes units to replace what will be used by a subsequent process. It is important to mention, though, that it is not a zero-inventory or stockless system per se, but it maintains only the necessary inventory between adjoining processes. The ideal of JIT is single unit production and conveyance among all processes in the entire manufacturing system. There are a number of other important elements that ensure its successful implementation. This includes *autonomation*—that is, autonomous defect control—which ensures that defective units are never moved from a given process to a subsequent one.

Kanban System

One of the key elements in JIT implementation is the kanban system, which is a signaling system for controlling the movement of parts among processes. It facilitates the transmission of information among processes; that is, it tells a preceding process to manufacture and replace the units of parts that have been used up by a subsequent process. Usually, a kanban contains the following information: (1) item name, (2) item identification number, (3) container type and capacity, and (4) name of preceding and/or subsequent process.

Because of the cascading format of manufacturing systems, the final assembly line serves as the initiator of the pull that is passed down to the other processes at the various levels. The system of kanbans ensures that they circulate between all pairs of processes, resulting in a scenario whereby all processes of the manufacturing system are somewhat chained together. Therefore, when there is a change in demand for the final products, the system causes this to be uniformly implemented across the various levels.

A wide variety of types of kanbans exist, whose specific uses are well suited to particular manufacturing conditions. However, the *production-ordering* kanban and the *withdrawal* kanban, the two main types of kanbans used, can be considered representative.

This pair of kanbans is illustrated in Fig. 9.4.1. An operator takes the number of withdrawal kanbans on the post, where they are stored, along with an equivalent number of empty containers or pallets to its immediate preceding process. He or she withdraws the desired units and detaches the production-ordering kanbans attached to each of these containers, replacing each with a withdrawal kanban. The detached production-ordering kanbans, which are then placed on their post in the preceding process, now become an order for this process to produce what has been withdrawn. The operator takes the withdrawn physical units to the subsequent process where the units are used. As the units are consumed in the subsequent process and the containers become empty, the attached withdrawal kanbans are placed on their post, pending when they are again collected for withdrawing units from the preceding process. An increase (decrease) in demand in the subsequent process will mean more (less) withdrawals, which will automatically elicit more (less) production at the preceding process.

Some very important rules guiding the use of kanban include (1) defective units must never be conveyed to the subsequent stage, (2) no withdrawal should be made without kanbans, and (3) the number of kanbans must be minimized. Since every full container carries a kanban, managers can be assured that the buildup of inventory does not exceed specified lim-

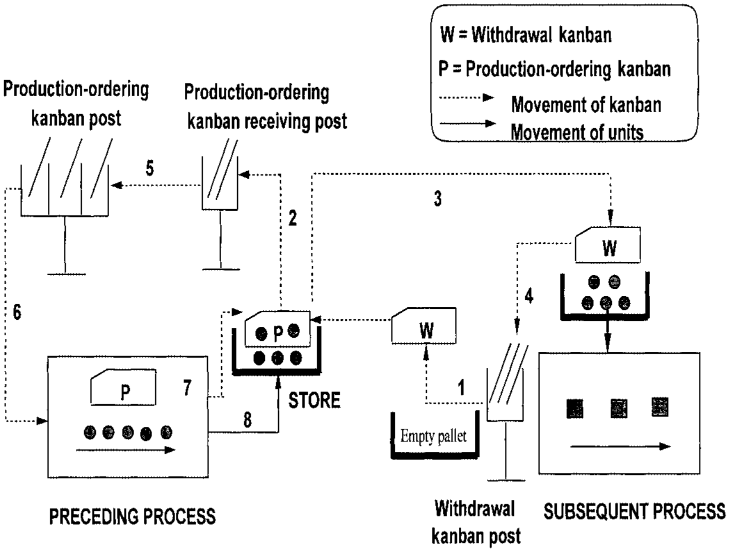

FIGURE 9.4.1 Representation of kanban system.

its. Usually, the total number of kanbans circulating between any two processes is kept constant, except when there is management intervention to either drain the system of kanbans or inject some more, if necessary.

Determining the Number of Kanbans. Two inventory systems used in the JIT system are the constant-quantity nonconstant cycle system (CQNCCS) and the constant-cycle nonconstant quantity system (CCNCQS), which respectively correspond to the constant order quantity and constant order cycle systems in the conventional inventory control system. While the former system (CQNCCS) is suitable for use within the plant, it is the latter that is used for parts delivery to the plant by outside suppliers, due mainly to geographical distance. When the distance between two processes is short (under CQNCCS) and the setup processes are improved, the total number of kanban circulating between them is given by the following expression:

$$N = \frac{\overline{Q}T(1+\alpha)}{C} \tag{9.4.1}$$

where $\overline{Q}$, T, α, and C are, respectively, the average daily demand, the lead time, a safety coefficient, and the container capacity. The lead time T is given by

$$T = \text{processing time} + \text{waiting time} + \text{conveyance time} + \text{kanban collecting time} \tag{9.4.2}$$

Under the CCNCQS, the total number of kanbans is expressed as:

$$N = \frac{Q(O+T+S)}{C} \tag{9.4.3}$$

where, Q, O, and S are, respectively, the daily demand, order cycle, and safety period. While the order cycle is the time interval spanning the points in time when two successive orders are issued, the lead time is the interval between placing an order and receiving delivery. Safety inventory period is the time interval corresponding to stock kept at the store to be prepared for exigencies such as machine trouble or defective items. An analysis is conducted to determine appropriate levels of stock.

Since unnecessary inventory is undesirable in a JIT environment, other steps are taken to provide for increased demand, instead of increasing the number of circulating kanbans. Primarily, attention is given to reduction of lead time when there is an increase in demand. If a process is incapable of making sufficient improvements to handle the new conditions, there will either be a line stop or there might be a need for overtime. Since this allows the problems to be easily visualized, concerted efforts are evoked to improve the process. However, when there is a decrease in demand, the cycle time of standard operations routine would increase, resulting in worker idle time. To avoid this, the number of workers in the process are reduced, with the excess capacity assigned to other processes. This is made possible by the multifunctional capabilities of workers in the JIT system.

PRODUCTION SMOOTHING

The JIT system seeks to smooth the manufacture of products in response to market demand. Demand for products is not usually uniform: there are certain periods in a month when the demand is high, while in others the demand is low. Production smoothing is therefore necessary to even out the product units manufactured. There are a number of dimensions to this concept.

Smoothing of the total production quantity is done to minimize the variance in total product output between two sequential time periods, for example, every day. The daily production would be obtained by dividing the estimated monthly demand of products by the number of operating days in the month. In one sense, we would still have some variation if monthly data were used as the basis for this smoothing, and it would seem better to use a shorter time span. Reducing it to weekly data would be more desirable on the one hand, but would, on the other, tend to erode the advantage of smoothing. The results from this smoothing are also used for planning the workforce and cycle time.

Smoothing the total production quantity would not be sufficient when a large number of a particular model is scheduled for production on a given day, while some other models either require very few units or are not scheduled for production at all on that day. Therefore, another important dimension is the *smoothing of each model's production quantity,* which causes each of the model variants to be uniform on a daily basis. In the case of automobile manufacturing, the term *model* is used in a fairly restricted sense and applies to a grouping of major components of the car such as body, engine, and transmission. (This is referred to as *katashiki* in Japanese.) Because these component specifications have a significant influence on the total assembly time of the products, this smoothing can help to smooth the load at the workstations in the assembly line.

The results of the preceding types of smoothing are not firm, but loose frameworks to prepare the materials and workforce, and hence prevent excessive variations that cannot be accommodated. Usually, the system is designed to be able to handle fluctuations of about ±10 percent in relation to estimated production.

The third dimension of smoothing involves the determination of the sequence schedule of product varieties for the mixed-model assembly line. At this point a number of goals may be considered, but the principal ones are the minimization of variation in parts utilization and the minimization of line stops due to uneven workload among the products.

SEQUENCING FOR JIT MIXED-MODEL ASSEMBLY LINES

Mixed-Model Assembly

Assembly systems, in which discrete item production occurs, are sometimes classified on the basis of the structural arrangement of the products that are to be assembled: (1) the single-model line, (2) the batch-model line, and (3) the mixed-model line. While the first type is a dedicated line on which only one model is assembled, the second line assembles more than one model, but it is done in such a way that all units of a particular model are completely assembled before commencing the assembly of another model. Although this line may have some advantages due to lower setup costs, it will generally generate large inventory carrying costs, which could make it more expensive overall. Furthermore, the lead time for product delivery would be long, which will directly affect efficient customer service.

Mixed-model assembly lines are used for the simultaneous manufacture of products that are essentially similar, but are characterized by a wide range of varying specifications—typical in the automotive, electronics, and telecommunication equipment industries. (A schematic representation of a mixed-model line is shown in Fig. 9.4.2.) This means that the models are assembled sequentially with, for example, a given unit of a particular model being "sandwiched" between two other models. Since the changeover cost is quite low, this type is often preferred to batch assembly. This mode of manufacture is used not only in JIT systems but also for conventional assembly lines.

JIT Assembly Sequencing, Waste Elimination, and Cost Reduction

Sequence scheduling is one of several phases in the design of a mixed-model production system. This phase is preceded by (1) the determination of a cycle time, (2) determination of the minimum number of processes, (3) representation of a precedent relationship between elemental

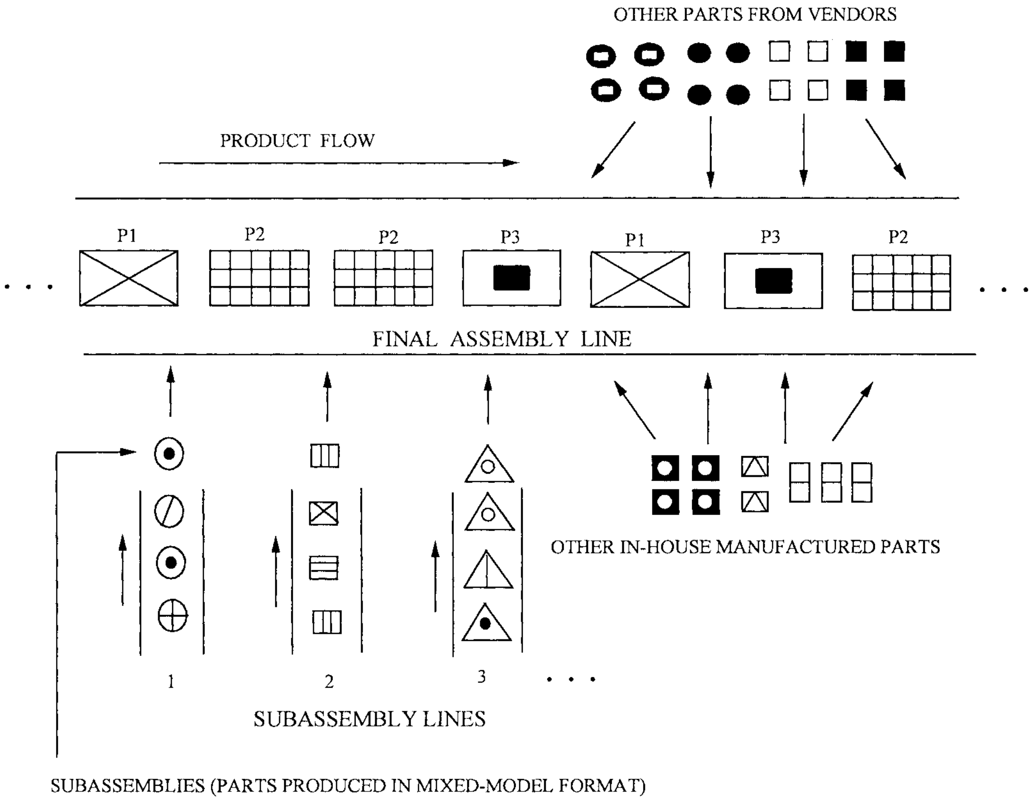

FIGURE 9.4.2 A typical mixed-model assembly line.

tasks, and (4) line balancing. The product units are usually not arranged for manufacture in a random manner, rather, they are properly arranged to optimize or satisfy certain criteria. For the JIT system, such a criterion is typically the minimization of variations in parts consumption compared with the average consumption. Another important criterion is the leveling of the load (total assembly time) on the assembly line or leveling of the workload requirements at the workstations. This latter goal is common between JIT and conventional assembly lines. Since the total number of feasible sequences is extremely large—especially in industrial situations—determination of optimum solutions is difficult. In general, heuristics (rules of thumb) are used to determine reasonably good solutions within acceptable computational time limits.

JIT is focusing on cost reductions leading to increased profit margins. By virtue of its pull characteristic, the sequence schedule for the mixed-model assembly line greatly impacts the achievement of cost reductions in the following ways:

- A smooth schedule primarily reduces the amount of inventory units that need to be kept for use on the final assembly line. This in turn reduces the necessary amount of inventory at all work centers in the multilevel production system. These reductions in inventory lower overall costs by eliminating the need for large storage facilities for the units, reducing the cost of capital associated with inventories, and eliminating unit obsolescence costs.
- A smooth schedule also impacts workforce planning for the assembly line, as well as all other work centers in the system. When the schedule is unbalanced, additional labor would have to be provided at the workstations or work centers to accommodate peak workloads.

This leads to excess labor during periods of limited workload, which leads to a waste of resources since these extra workers still have to be paid.

- Line balancing alone does not solve the workload problem at the workstations, which is a formidable task for mixed-model lines. Therefore, an unbalanced schedule increases the probability of assembly line stops. These result in lost production time, which have cost implications for the firm. Quite often, for example, overtime work has to be scheduled—at a higher cost—to finish up uncompleted work associated with these line stops.

Mathematical Models for JIT Sequence Scheduling

The models that have been used to describe the JIT sequencing problem mainly seek to minimize the deviation from an average, which depends on the goal in question. For smoothing of (1) parts consumption, the model seeks to minimize the difference between actual and mean parts consumption. Other goals are meant to minimize deviation from the mean of (2) product rate, (3) product load, and (4) subassembly load.

Single Objective Problems—Fundamental Notations. Assume a total of Q product units that are composed of Q_i ($i = 1, 2, \ldots, \alpha$) units with each α product types (models) to be sequenced on a final assembly line. The scheduling horizon can then be considered to be made up of Q stages ($k = 1, 2, \ldots, Q$), where each stage corresponds to the positioning of a single unit of product in the sequence. The cumulative amount of the product type i at stage k is given by $P_{ik} = P_{i,k-1} + 1$ if i is the product scheduled at stage k, but $P_{ik} = P_{i,k-1}$ otherwise. Hence, the cumulative amount of a generic product, i' may be expressed as, $P_{i'k} = P_{i',k-1} + J_{ii'}$ where $J_{ii'}$ is an indicator function that takes on the value 1 when $i' = i$, but 0 otherwise (i here denotes the product considered as scheduled for stage k).

Parts Usage Smoothing. Let b_{ij} units of part type j be required for making 1 unit of product type i. Then, the total number of part type j required by all products would be given by $N_j = \sum_{i \neq 1}^{\alpha} Q_i b_{ij}$. Also the cumulative number of part type j ($j = 1, 2, 3, \ldots, \beta$) at a stage k when product type i occupies the kth position may be expressed as $X_{jk} = X_{j,k-1} + b_{ij}$, where $X_{j0} = 0$. Let R_{k-1} be the cumulative number of all part types used up to stage $k - 1$. Then the cumulative amount of parts used at stage k if product i is scheduled at stage k would be given by $t_{ik} = R_{k-1} + \sum_{j=1}^{\beta} b_{ij}$, while the total number of parts used by all products would be $T = \sum_{j \neq 1}^{\beta} N_j$. Our desire is to ensure that the actual quantity of a given part type required is as close as possible to the average (ideal) requirement over the entire scheduling horizon. This may be expressed as follows (S is a sequence):

$$\underset{S}{Minimize} \left| \frac{{}^{k}N_j}{Q} - X_{j,k-1} - b_{ij} \right| \; k = 1, 2, \ldots, Q \text{ for each } j(1 \sim \beta) \tag{9.4.4}$$

or

$$\underset{S}{Minimize} \left| \frac{t_{ik}N_j}{T} - X_{j,k-1} - b_{ij} \right| \; k = 1, 2, \ldots, Q \text{ for each } j(1 \sim \beta) \tag{9.4.5}$$

While the first objective function relates mean part consumption to actual part consumption based on the ratio of products scheduled at a given stage to the total production quantity, the second relates it on the basis of the ratio of the number of units of parts used at a given stage to the total number of units of parts required.

It can be noticed that the objective expressed is in a sense a multicriterion problem, since we want to simultaneously minimize the variation for each part. It is somewhat difficult to have a unique sequence S, which minimizes the function at each stage for each of the parts. A generally accepted procedure for combining the objectives is to represent each part type as a coordinate of a point in β-dimensional space. Two points are thus used, one represents the average consumption state while the other represents the actual consumption state, with the aim to minimize the Euclidean distance between these points. In other words, at any stage we have these coordinates for the first objective function as $A = (kN_1/Q, kN_2/Q, \ldots\ldots, kN_\beta/Q)$ and $B = (X_{1k}, X_{2k}, \ldots\ldots, X_{\beta k})$, which results in the following objective functions:

$$\Delta_{ki}^{PTU} = \sqrt{\sum_{j=1}^{\beta} \left(\frac{kN_j}{Q} - X_{j,k-1} - b_{ij} \right)^2} \tag{9.4.6}$$

or

$$\Delta_{ki}^{PTU} = \sqrt{\sum_{j=1}^{\beta} \left(\frac{t_{ik}N_j}{T} - X_{j,k-1} - b_{ij} \right)^2} \tag{9.4.7}$$

Our parts usage smoothing problem under the preceding Euclidean distance–based formulation becomes

$$\underset{S}{Minimize} \sum_{k=1}^{Q} \Delta_{ki}^{PTU} \tag{9.4.8}$$

subject to

$$0 \le P_{ik} - P_{i,k-1} \le 1 \; P_{ik} \text{ (integer) } i = 1, 2, \ldots., \alpha; \text{ and } k = 1, 2, 3, \ldots, Q \tag{9.4.8a}$$

$$\sum_{i=1}^{\alpha} P_{i,k} = k \quad k = 1, 2, 3, \ldots, Q \tag{9.4.8b}$$

$$P_{i0} = 0,\ P_{iQ} = Q_i \tag{9.4.8c}$$

Product Rate Variation Smoothing

$$\Delta_{ki}^{PRL} = \sqrt{\sum_{i'=1}^{\alpha} \left(\frac{kQ_{i'}}{Q} - P_{i',k-1} - J_{ii'} \right)^2} \tag{9.4.9}$$

where

$$P_{i'k} = P_{i',k-1} + J_{ii'}$$

$$k = 1, 2, 3, \ldots\ldots, Q;\ i' = 1, 2, 3, \ldots., \alpha$$

Product Load Smoothing. The product load objective is formulated in a number of different ways, each of which is based on the Euclidean distance concept mentioned previously. These are as follows:

a. The models are classified into load classes based on the total time for assembly of each model on the line. These classes are then treated as "parts," with the application of the same procedure used for parts usage smoothing.

b. A product rate variation based function is expressed in terms of the total assembly time of each of the models.

c. By using the assembly time of each model, at each workstation on the assembly line.

Formula (a)

$$\Delta_{ki}^{PRL} = \sqrt{\sum_{p=1}^{\mu} \left(\frac{kT_p}{Q} - Y_{p,k-1} - c_{ip} \right)^2} \tag{9.4.10}$$

where

$$Y_{pk} = Y_{p,k-1} + c_{ip}$$

$$k = 1, 2, 3, \ldots\ldots, Q;\ p = 1, 2, 3, \ldots., \mu$$

where c_{ip} is the total assembly time for product i, which belongs to class p. Actually, the value of c_{ip} is 0 if model i does not belong to class p. Y_{pk} and T_p are, respectively, the cumulative load for class p up to stage k, and the total load for class p. μ is the total number of load classes.

Formula (b)

$$\Delta_{ki}^{PRL} = \sqrt{\sum_{i'=1}^{\alpha} \tau_{i'}^2 \left(\frac{kQ_{i'}}{Q} - P_{i',k-1} - J_{ii'} \right)^2} \tag{9.4.11}$$

where $\tau_{i'}$ is the total assembly time for product i'.

Formula (c)

$$\Delta_{ki}^{PRL} = \sqrt{\sum_{w=1}^{n} \left(\frac{kH_w}{Q} - C_{w,k-1} - \tau_{iw}^{s} \right)^2} \tag{9.4.12}$$

or

$$\Delta_{ki}^{PRL} = \sqrt{\sum_{w=1}^{n} \left(\frac{m_{ki}H_w}{M} - C_{w,k-1} - \tau_{iw}^{s} \right)^2} \tag{9.4.13}$$

where τ_{iw}^{s} and C_{wk} are, respectively, the assembly time for product i and the actual time required to assemble the first k product units at workstation w. m_{ki} is the total time required to assemble the first k units given that product i is scheduled at stage k. H_w is the cumulative time required to assemble all the product units at workstation w and M is the total time required to assemble all the product units at the n workstations.

Subassembly Load Smoothing. This formula that seeks to minimize the workload among subassemblies on a given subassembly line is expressed as follows:

$$\Delta_{ki}^{SAL} = \sqrt{\sum_{m=1}^{\gamma} \left(\frac{kU_m}{Q} - Z_{m,k-1} - d_{im} \right)^2} \tag{9.4.14}$$

where

$$Z_{mk} = Z_{m,k-1} + d_{im}$$

$$k = 1, 2, 3, \ldots\ldots, Q;\ m = 1, 2, 3, \ldots\ldots, \gamma$$

where d_{im} is the load on subassembly line m when product i is scheduled, and Z_{mk} and U_m are respectively the cumulative load for m at stage k and the total load for m.

The optimization problem for each of these other goals follow directly from that for the parts smoothing problem stated previously. That is, we seek for a given objective the sequence of products that minimizes the sum of variations over the entire planning horizon Q. We observe that the objectives have been expressed in their root forms, but the nonroot forms may be used instead.

Other Formulas for Level Schedules. Although a number of objectives may be considered for determining the sequence, one aspect that has attracted much attention is the issue of obtaining a level schedule of products, because a level schedule impacts on how well the sequence affects other objectives. The problem of determining the sequence by taking only the product level into consideration is sometimes referred to as the *product rate variation* (PRV) problem. Determining the sequence by output elements—parts smoothing in particular—is referred to as the output rate variation (ORV) problem. Indeed, the product rate variation smoothing objective formula (9) is one way of expressing the PRV objective. This sum-of-deviation formula based on Euclidean distance would generally produce sequences that are smooth on the average, but there is the possibility of having relatively large deviations in some time periods. Therefore, an alternative objective based on minimizing the maximum deviation has been proposed [1] to ensure that a smooth schedule is produced in every time period. Thus the problem is formulated as

$$^{Minimize}\underset{ik}{Maximum}\left|\frac{kQ_i}{Q} - P_{ik}\right| \tag{9.4.15}$$

$$i = 1, 2,...., \alpha; \text{ and } k = 1, 2, 3, \ldots, Q$$

subject to the constraints in Eqs. (9.4.8a), (9.4.8b), and (9.4.8c).

The PRV problem has been related to a single machine scheduling problem with earliness and tardiness penalties, where the earliest due date (EDD) rule is shown to yield optimum sequence for the latter objective. Since this objective is intuitively similar in intent to the PRV problem, by treating each unit of product as a separate job and utilizing their due dates, a suitable sequence can be obtained. Although this sequence cannot be guaranteed to be optimal for the original formulation, it has been shown to produce very good sequences at a small computational cost. Given that the time at which the sth copy of product i is needed and when it is actually produced are t_{si} and T_{si} respectively, the equivalent single machine scheduling problem may be expressed as

$$\underset{S}{Minimize} \sum_{i=1}^{\alpha} \sum_{s=1}^{Q} (T_{si} - t_{si})^2 \tag{9.4.16}$$

where t_{si} is computed as follows:

$$t_{si} = \frac{(s - 1/2)Q}{Q_i} \quad i = 1, 2, \ldots, \alpha; s = 1, 2,...., Q_i \tag{9.4.17}$$

The PRV problem has also been reformulated as an assignment problem [2] by considering penalty costs attributable to each copy of the product types when it is located in a position other than its ideal position (that is, either too early or too late). This cost is zero for the case when a particular copy is appropriately assigned. It has also been shown that an optimal solution for the original problem can be constructed from the optimal solution of the equivalent assignment problem.

Multilevel and Multicriterion Problems. Most manufacturing systems are characterized by a multiechelon structure whereby certain units at a given level are used to manufacture various types of units at a higher level. This continues up until the final level, where we then have the final products. Taking automobile manufacture as an example, various types of engines are used for a particular car series, and each of these engines has parts used in common such as pistons. These, in turn, are made from some components or materials that may be of different characteristics. The multilevel problem entails finding the sequence of products that would ensure that the actual requirements for all items at all levels do not vary so much from their respective averages over the entire planning horizon. One method for jointly treating variation at these levels uses a weighted function, comprising the terms for all levels. Expressed mathematically, we have

$$\underset{S}{Minimize} \sum_{k=1}^{Q} \sum_{v=1}^{L} \sum_{j=1}^{n_v} W_v \left(\frac{kq_{jv}}{Q} - x_{jvk}\right)^2 \tag{9.4.18}$$

or

$$\underset{S}{Minimize} \sum_{k=1}^{Q} \sum_{v=1}^{L} \sum_{j=1}^{n_v} W_v \left(\frac{C_{vk}q_{jv}}{T_v} - x_{jvk}\right)^2 \tag{9.4.19}$$

where x_{jvk} is the actual number of units of j at level v used by all products from stage 1 through k, C_{vk} is the cumulative number of all units of level v used up to stage k, q_{jv} is the total quantity of unit j at level v, and T_v is the total number of units at level v needed by all products. W_v is the weight, which indicates the relative importance of a given level. Any level is discarded from the model simply by setting its weight W_v to 0. While the first equation considers the fraction of units on a time basis (where the horizon of Q units of products can be taken as Q time units), the lat-

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ter (which is a generalization of the former) considers the actual fraction of units at the levels. One requirement that is considered necessary under this formulation is the need to have a sequence that balances smoothing across all levels. Weights are chosen either in proportion to the number of types of units or the total quantity of units at each level, and this procedure has been reported to work reasonably well. However, the weights, which are an essential part of the model, would need to be carefully chosen after all the relevant data are known. The difficulty associated with appropriately determining these weights has yet to be completely resolved.

The multicriterion problem, as the name implies, is one that simultaneously addresses two or more criteria to determine the sequence, and the aforementioned multilevel problem is a special case of this. Multicriterion is used here on a macrodimension as compared with, for example, the parts usage smoothing problem (which involves the subgoals of smoothing each part). Consider the problem of simultaneously smoothing parts usage as well as product load. These two goals are the most important goals addressed in mixed-model assembly lines in a JIT environment. The first of these is the core of the JIT philosophy, while the second, which is common to conventional assembly lines, relates to how well the product units are introduced to prevent line stoppages, especially at bottleneck stations. The difficulty in effectively balancing the line by *equal* or *nearly equal* task allocations at the workstations, especially for mixed-model lines, makes this an important goal to consider. Indeed, if units with large work contents follow consecutively, then there is a greater tendency to have line stoppages, since the operator would not be able to complete the assigned task within the cycle time. On the other hand, units of relatively small assembly times following consecutively would result in operator idle time. A balance achieved through an appropriate sequence is necessary since both lost production time and idle time have cost implications for the manufacturer. The use of weights for solving this problem would not be particularly appropriate in view of the scaling problem arising from different units of measurement and the difficulty of actually estimating these weights for practical scheduling.

Solution Methodologies

Optimization Procedures. The space of feasible sequences would be very large; therefore, explicit enumeration would be unfeasible, except for very small problem instances. Therefore, implicit enumeration techniques such as dynamic programming and branch-and-bound techniques are mostly used. Some of the procedures for solutions to problems that have been proposed in the literature are described in the following sections.

Nearest Integer Point Algorithm (NIPA)—PRV. The NIPA is one solution method to the PRV problem. This algorithm is a search procedure that looks for the integer point that is closest to the average point (which is real), where the latter's coordinates are the average production values for the various product types, given that k units of all product types are scheduled [3]. Let the average and integer points be respectively denoted by $V_k = (v_{k1}, v_{k2}, v_{k3}, \ldots, v_{k\alpha}) \in R^{\alpha}$ and $W_k = (w_{k1}, w_{k2}, w_{k3}, \ldots, w_{k\alpha}) \in Z^{\alpha}$. The procedure solves for each k,

$$\underset{Wk}{Minimize} \sum_{i=1}^{\alpha} (w_{ki} - v_{ki})^2 \tag{9.4.20}$$

We define $N_k = k = \sum_{i=1}^{\alpha} v_{ki}$ and $S_k = \sum_{i=1}^{\alpha} w_{ki}$.

ALGORITHM NIPA (PHASE 1): Do for $k = 1, Q$.

Step 1. Calculate $v_{ki}\ \forall\ i$.

Step 2. Determine for each i, w_{ki} such that $|w_{ki} - v_{ki}| \le 0.5$.

Step 3. Calculate S_k.

Step 4. If $N_k - S_k > 0$ go to step 5, else if $N_k - S_k < 0$ go to step 6, else $N_k = S_k$ hence STOP. ($W_k = (w_{k1}, w_{k2}, w_{k3}, \ldots, w_{k\alpha})$ is the nearest integer point to V_k.)

Step 5. Increment w_{ki} by 1 for product *i,* which minimizes $w_{ki} - v_{ki}$, then return to step 3.

Step 6. Decrement w_{ki} by 1 for product *i,* which maximizes $w_{ki} - v_{ki,}$ then return to step 3.

The sequence obtained by this routine may be *superoptimal* if infeasibility results for any stage *k,* that is, if for some *i* at some *k,* $w_{ki} < w_{k-1,i}$. This would imply that an already manufactured product is destroyed at a latter stage. The sum of variations for the routine is a lower bound on the optimum objective value. Both values are equal if the sequence obtained by the procedure is feasible. The second phase of the algorithm is meant to correct infeasibilities for all affected products over pertinent stages.

ALGORITHM NIPA (PHASE 2)

1. Determine the number of products *n* for which $w_{t,i} < w_{t-1,i}$.
2. Do for all infeasible *i:* Reschedule all stages between $(t - n)$ and $(t + 1)$ by considering all possibilities (explicit enumeration) of partial sequences that start from $(t - n - 1)$ and end at $(t + 1)$. The one that minimizes the variation over the rescheduled region is connected to the other parts of the schedule to form the optimum sequence.

This algorithm works well, but would require a significant amount of computations if the number of infeasible products is large. Heuristics have also been proposed to mitigate this, but they do not guarantee optimality.

Branch-and-Bound Algorithm—PRV. An alternative solution method to the PRV problem is the branch-and-bound solution methodology [4]. This method, which is linked to NIPA and based on analytical results of the properties of the optimal production path, requires the determination of both a lower bound and an upper bound on the optimum solution to the problem. The lower bound is obtained by the application of Langrangean relaxation to the original nonlinear integer problem, where the Lagrangean multipliers are obtained by solving associated linear programming problems for each infeasible sequence position.

The upper bound determination involves the selection of the product (at each stage of the infeasible region), which minimizes the variation at three successive stages instead of one or two stages used previously. The implementation of the procedure involves the use of the depth-first search strategy such that the pending node that has the smallest lower bound among all those of the same level is chosen for branching. Any node for which the computed lower bound value exceeds the upper bound value is *fathomed.*

Dynamic Programming (DP) Algorithm—PRV and ORV. The DP formulation of the problem involves determining the variation between average and actual product (part) for all the possible points in the state space, and then searching for the optimum path through these states [5]. Let us define $\mathbf{v}_i$ as the $\alpha \times 1$ unit vector representing product type *i.* The stage variation for a given state **Y** is given for the problems as

PRV problem:

$$\mu(Y) = [\sum_{i=1}^{\alpha} (kQ_i/Q - y_i)^2]^{1/2} \tag{9.4.21}$$

ORV problem:

$$\mu(Y) = [\sum_{j=1}^{\beta} (kN_j/Q - \sum_{Y} b_{ij})^2]^{1/2} \tag{9.4.22}$$

where y_i is the number of product types *i* for the given state **Y** and $\sum_Y b_{ij}$ is the total number of units of part type *j* required for all products in **Y**. The minimum cumulative variation for the states can then be described by the following recursive equation:

$$\gamma(Y) = \text{Minimum } [\gamma(Y - v_i) + \mu(Y)] \ \forall \text{ feasible } i \tag{9.4.23}$$

where

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$$\gamma(\varnothing) = [\gamma(Y(y_1, y_2, \ldots, y_\alpha)] = 0; y_i = 0 \; \forall \; i \tag{9.4.24}$$

and

$$|Y| = \sum_{i=1}^{\alpha} y_i = k \tag{9.4.25}$$

Let Ω_k be the set of feasible states for a stage k. $\gamma(|Y| = Q)$ is the optimum objective value. Other states on the optimum path(s), which are those that minimize $\gamma(Y)$ for each stage, and the corresponding products are identified by working backwards from stage Q to 1. The computational requirement for this procedure is $O(\alpha \prod_{i=1}^{\alpha} (Q_i + 1))$, which, though quite large for even moderate-sized problem instances, is far more computationally efficient than explicit enumeration.

Bounded Dynamic Programming—ORV. This is a hybrid procedure, which is essentially based on the DP procedure, but some properties of the graph associated with the problem are exploited to obtain bounds [6]. These bounds are incorporated into the solution procedure, the purpose being to eliminate at every level vertices of the graph that cannot lead to the optimum solution. In other words, it makes use of two values for a vertex, one of these being the value for the best path leading to it, while the other is a lower bound on the completion of the path. If the sum of these values exceeds an upper bound value (objective value of a good heuristic), then the path represented by this vertex cannot lead to the optimum solution, and is thus eliminated.

In view of the substantial number of vertices that would need to be considered at certain levels, including all vertices would be computationally intensive. Therefore, the procedure is fine-tuned to consider at each stage only potentially good vertices within a moving window of given width. The algorithm would generally produce sequences that are better than those corresponding to the initial upper bound. If it ends without leading to the optimum (ascertained by some rule), the procedure is reiterated by using the improved objective value as a new upper bound. The performance of the procedure depends on the bound and the quality of the initial upper bound solution; therefore, it is not quite clear whether it would have significant computational time advantage over the direct use of dynamic programming. However, savings in storage requirements may be anticipated, since not all vertices need to be examined.

Heuristics. Most of the heuristics used for solving the JIT assembly line sequencing problem belong to the class of procedures referred to as "greedy algorithms." These procedures, which are based on human intuition, attempt to do the best they can locally. Although they are not guaranteed to yield optimal sequences, they generally produce good sequences with modest computational effort.

Goal Chasing (Single-Step Heuristic). This is the classical solution procedure proposed by Toyota Motor Corporation for the sequencing problem [7]. The routine is given for the parts usage smoothing problem as follows:

Step 1. Set $k = 1, X_{j,k-1} = 0, (j = 1, 2, \ldots., \beta), S_{k-1} = \{1, 2, \ldots, \alpha\}$.

Step 2. Set in the kth position of the sequence schedule the product A$\{i^*\}$, which minimizes the distance Δ_{ki}^{PTU}. That is, we have $\Delta_{ki}^{PTU*} = \text{Minimum } \Delta_{ki}^{PTU}, i \in S_{k-1}$.

Step 3. If all units of the product type A$\{i^*\}$ have been placed in schedule, then set $S_k = S_{k-1} - \{i^*\}$. If some units of the product type A$\{i^*\}$ are still yet to be placed in schedule, then set $S_k = S_{k-1}$.

Step 4. If $S_k = \varnothing$ (empty set), the algorithm ends.

If $S_k \neq \varnothing$, then compute $X_{jk} = X_{j,k-1} - b_{i^*j}$ $(j = 1, \ldots, \beta)$ and return to step 2 by setting $k = k + 1$.

Two-Step Heuristic. This heuristic, which was proposed by Miltenburg [3], seeks to minimize the myopic decision tendency inherent in the one-step procedure, by using a look-ahead principle to determine products stage by stage. Among products whose units are yet to be completely placed in schedule the heuristic selects for a given stage the one that minimizes the sum of variation at the stage in question and the subsequent one. It generally produces better sequences than the one-step procedure, at a relatively higher computational cost. (The computational requirements of the two-step procedure are of the order of α times that of the one-step procedure.) This results in the following rule for parts usage smoothing:

Step 1. Set $k = 1$, $X_{j,k-1} = 0$, $(j = 1,\dots., \beta)$, $S_{k-1} = \{1, 2, \dots, \alpha\}$.

Step 2. For each scheduled product r at stage k, tentatively schedule r for this stage and then calculate Δ_{kr}^{PTU}; temporarily update the cumulative consumption of each part type.

Step 3. Given that r is scheduled at stage k, tentatively schedule product s^* at stage $k + 1$ as the one that minimizes $\Delta_{(k+1)s}^{PTU}$.

Step 4. Calculate $V_k(r) = \Delta_{kr}^{PTU} + \Delta_{(k+1)s^*}^{PTU}$.

Step 5. Permanently schedule for stage k, the product r^* that minimizes $V_k(r)$.

Step 6. If all units of the product type r^* have been placed in schedule, then set $S_k = S_{k-1} - r^*$, else set $S_k = S_{k-1}$.

Step 7. If $S_k = \varnothing$ (empty set), the algorithm ends. If $S_k \neq \varnothing$, then permanently update cumulative consumption of each part type, return to step 2 by setting $k = k + 1$.

Earliest Due Date (EDD) Heuristic. This heuristic makes use of the result of optimum sequencing under the EDD rule for the single machine scheduling problem, which is intuitively similar to the JIT sequencing problem [8]. In principle, it addresses the PRV problem because only the product level is considered. However, the result derived has sometimes been reported to be satisfactory for the multilevel problem. The steps for the heuristic are

Step 1. Using Eq. (17) compute the ideal due date t_{si} for all copies of all product types.

Step 2. Obtain the sequence by sorting the results of step 1 in ascending order of due date.

Parametric Sequencing Procedure. The multigoal problem is sometimes addressed by using a multiattribute function formula, where weights representing the preference for the goals are assigned accordingly [9]. However, these weights may be difficult to estimate for practical assembly line sequencing problems, primarily because of the differences in the units of measurement for the goals.

The parametric procedure (see Fig. 9.4.3) is based on a different framework, which does not require the aggregation of goals and use of weights. Rather, the goals are treated in tandem based on information on the relative preference structure. It is essentially a greedy procedure, which seeks products stage by stage that satisfy a dynamic limiting condition for as many goals as possible. At each stage of the greedy routine, a bound is computed for each goal using the following equation:

$$OV_{g(\text{lim})}^{k} = OV_{g(\text{min})}^{k} + \theta(OV_{g(\text{max})}^{k} - OV_{g(\text{min})}^{k}) \tag{9.4.26}$$

where $OV_{g(\text{min})}^{k}$ and $OV_{g(\text{max})}^{k}$ are respectively the minimum and maximum value at stage k for the set of products that are yet to be scheduled after stage $k - 1$. (The cardinality of this set at stage 1 is α but decreases by 1 each time all units of a particular product type have been placed in schedule.) The allowability factor θ is varied parametrically between 0 and 1, and it regulates feasibility of the unscheduled products, which may be considered at each stage. Each value corresponds to one replication and the necessary number of values of θ (replications) depends on the number of product types. While too many values would not be computationally efficient, too few values would affect the quality of the results. A trade-off is necessary to obtain satisfactory results. The routine checks each of the schedulable products and selects the ones that fall within the bound of as many goals as possible. The implementation of this strategy is as follows. If there is a single product that satisfies the bounds for all goals, it is sched-

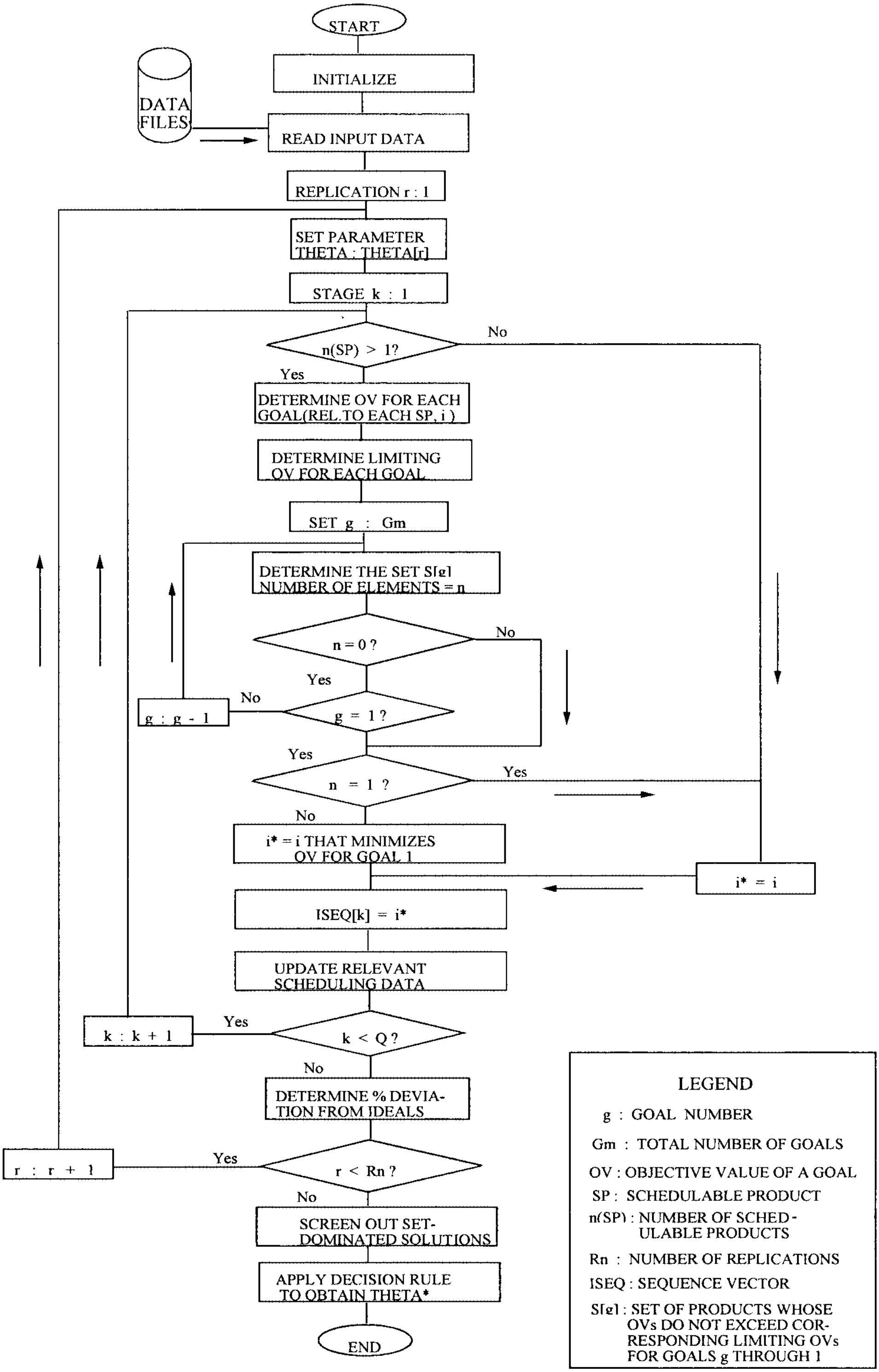
START
INITIALIZE
DATA FILES
READ INPUT DATA
REPLICATION r : 1
SET PARAMETER THETA : THETA[r]
STAGE k : 1
n(SP) > 1?
No
Yes
DETERMINE OV FOR EACH GOAL(REL.TO EACH SP, i)
DETERMINE LIMITING OV FOR EACH GOAL
SET g : Gm
DETERMINE THE SET S[g] NUMBER OF ELEMENTS = n
n = 0 ?
No
Yes
g : g - 1
No
g = 1 ?
Yes
n = 1 ?
Yes
No
i* = i THAT MINIMIZES OV FOR GOAL 1
i* = i
ISEQ[k] = i*
UPDATE RELEVANT SCHEDULING DATA
k : k + 1
Yes
k < Q ?
No
DETERMINE % DEVIATION FROM IDEALS
r : r + 1
Yes
r < Rn ?
No
SCREEN OUT SET-DOMINATED SOLUTIONS
APPLY DECISION RULE TO OBTAIN THETA*
END
LEGEND
g : GOAL NUMBER
Gm : TOTAL NUMBER OF GOALS
OV : OBJECTIVE VALUE OF A GOAL
SP : SCHEDULABLE PRODUCT
n(SP) : NUMBER OF SCHEDULABLE PRODUCTS
Rn : NUMBER OF REPLICATIONS
ISEQ : SEQUENCE VECTOR
S[g] : SET OF PRODUCTS WHOSE OVs DO NOT EXCEED CORRESPONDING LIMITING OVs FOR GOALS g THROUGH 1

FIGURE 9.4.3 Flowchart for the parametric procedure.

uled for that stage. If there are two or more products, the one that minimizes the objective value for the most important goal (goal 1) is chosen. If no product satisfies the bound for all goals, the least important goal is dropped from consideration, and the feasibility is checked for the remaining higher order goals. This deletion of goals (starting from the least order goal upward) continues until a point is reached where at least one product that satisfies a group of goals can be found. In the worst case, only the most important goal is left, and if there is only one product satisfying its bound, it is chosen; otherwise, the one that minimizes the objective value for this goal is chosen.

After all replications, the next phase is the screening phase, where all set-dominated sequences are screened out. A sequence is set-nondominated if there exists no other sequence (among those generated for all values of θ), for which the objective value is superior in at least one goal. The decision phase comes next, and it involves the application of a suitable decision rule. Any one of the two rules proposed for this, percentile-cut (PC) or minimax rule, is applied to the set-nondominated solutions to obtain the appropriate θ. With this value known, the sequence it corresponds to is the desired sequence, and it can be easily obtained by running the routine using this value of θ.

Expert Systems. Expert systems are systems, which are designed to use expert knowledge in a particular field of endeavour to solve practical problems. Successful applications in medical diagnoses, mineral exploration, and so on have been reported. The bicriterion JIT problem involving parts usage smoothing and product load smoothing (in the automobile industry in particular) has also been addressed by using expert systems. This knowledge, which is obtained from assembly line personnel, is represented in the form of IF THEN rules and are used in deciding the sequence of products. The four main concepts on which these rules are based are appearance ratio control, continuation control, interval control, and weighting control. While the first one relates to parts usage smoothing, the others relate to product load smoothing. For example, we may have a rule as follows: "*If* the specification of a car is x and the continuation of this specification does not exceed y, *then* introduce the car."

Metaheuristics. Metaheuristics are general purpose procedures used for solving combinatorial optimization problems. These include procedures such as simulated annealing, tabu-search, and genetic algorithms. Their main merit is their ability to incorporate mechanisms, which prevent the solution procedure from getting stuck in a local optimum. However, they generally require significantly large amounts of computation to yield good solutions. This apparently explains why not much has been reported in the literature about their application to this problem.

Hybrid procedures that use any of these metaheuristics as a base, while incorporating the presently applied *successive augmentation principle*—as exemplified by Toyota's single-step and Miltenburg's two-step rules—would be useful. This would exploit the inherent properties of the basic procedures to produce good solutions with modest computational requirement.

Note. In addition to the preceding heuristics, others based on beam search, preservation of the product rate, and symmetrical assignment of product units over the planning horizon have been reported to have a tendency of improving smoothing in parts utilization.

Numerical Example. To illustrate some of the points discussed previously, we consider the scheduling of 10 units of products, comprised of 2, 3, and 5 units each of three product types, the aim of which is to smooth parts consumption. The bill of materials is as indicated in Table 9.4.1. Without loss of generality, in this example we use the root form of the Euclidean distance formulation of the objectives. The number of part j required by all products would be $[N_j] = [Q_i][b_{ij}]$. That is,

$$[2\ 3\ 5]\begin{bmatrix} 1 & 0 & 1 & 1 \\ 1 & 1 & 0 & 1 \\ 0 & 1 & 1 & 0 \end{bmatrix} = [5\ 8\ 7\ 5]$$

which implies that a total of 5, 8, 7, and 5 units of part types 1, 2, 3, and 4 are respectively required by all products.

TABLE 9.4.1 Data for Sample Problem

Product composition structure: 2 3 5				
Product variety/part variety	1	2	3	4
1	1	0	1	1
2	1	1	0	1
3	0	1	1	0

DP Solution. There are a total of $(2 + 1)(3 + 1)(5 + 1) = 72$ states. Using the nonroot form of equation (23), we have the variation for the states (1 0 0) and (1 1 1) as

$$\mu(1\ 0\ 0) = [(1 \times 5/10 - 1)^2 + (1 \times 8/10 - 0)^2 + (1 \times 7/10 - 1)^2 + (1 \times 5/10 - 1)^2]^{1/2} = 1.1091$$

$$\mu(1\ 1\ 1) = [(3 \times 5/10 - 2)^2 + (3 \times 8/10 - 2)^2 + (3 \times 7/10 - 2)^2 + (3 \times 5/10 - 2)^2]^{1/2} = 0.8185$$

The state (1 0 0) is preceded only by (0 0 0), whereas (1 1 1) is preceded by three states—{(0 1 1), (1 0 1) and (1 1 0)}—each corresponding to the deletion of one product unit. Therefore, $\gamma(1\ 0\ 0) = 1.1091$, while $\gamma(1\ 1\ 1) = \text{Minimum}\ \{1.3594 + 0.8185, 1.6422 + 0.8185, 2.6024 + 0.8185\} = 2.1779$. Detailed results for all the states are given in the table in the Appendix. Starting from the final state (2 3 5), we identify the states on the optimal path and the associated products. Thus, the optimal sequence is {3-2-1-3-2-3-3-1-2-3} or {3-2-1-3-3-2-3-1-2-3} with an objective value of 5.7874.

Goal Chasing Method

$$X_{j0} = 0\ \forall\ j$$

Given that product 1 is scheduled for stage 1 we have the deviation as

$$\Delta_{11}^{PTU} = \sqrt{\left(\frac{1\times 5}{10} - 0 - 1\right)^2 + \left(\frac{1\times 8}{10} - 0 - 0\right)^2 + \left(\frac{1\times 7}{10} - 0 - 1\right)^2 + \left(\frac{1\times 5}{10} - 0 - 1\right)^2} = 1.1091$$

Computing for this we have the deviations for products 2 and 3 respectively as 1.0149 and 0.7937. Thus, the minimum deviation is Minimum [1.1091, 1.0149, 0.7937] = 0.7937, indicating that product 3 should be scheduled for stage 1. Noting that $X_{jk} = X_{j,k-1} + b_{3j}$, we update cumulative parts consumption as follows: $X_{11} = 0 + 0 = 0$, $X_{21} = 0 + 1 = 1$, $X_{31} = 0 + 1 = 1$, $X_{41} = 0 + 0 = 0$.

Assuming product 3 is scheduled for stage 2:

$$\Delta_{23}^{PTU} = \sqrt{\left(\frac{2\times 5}{10} - 0 - 0\right)^2 + \left(\frac{2\times 8}{10} - 1 - 1\right)^2 + \left(\frac{2\times 7}{10} - 1 - 1\right)^2 + \left(\frac{2\times 5}{10} - 0 - 0\right)^2} = 1.5875$$

The deviations at stage 2 for products 1 and 2 are respectively 0.8485 and 0.5657. Therefore, the minimum deviation for this stage is Minimum [0.8485, 0.5657, 1.5875] = 0.5657, indicating that product 2 should be scheduled at stage 2. Prior to stage 3, we again update the cumulative parts consumption; thus, $X_{12} = 0 + 1 = 1$, $X_{22} = 1 + 1 = 2$, $X_{32} = 1 + 0 = 1$, $X_{42} = 0 + 1 = 1$. Detailed results are indicated in Table 9.4.2. The products chosen are identified by the asterisks on the minimum stage values. Notice that there is a tie at stage 5. Selecting product 3 instead of 2 would lead to the sequence 3-2-1-3-3-2-3-1-2-3, which has the same overall objective value.

Nearest Integer Point Algorithm. The application of the nearest integer point algorithm to this problem (involving only the products) produces the same sequence as the previous two procedures. Since infeasibility does not occur at any stage, this sequence is optimal for the PRV problem as well, and the second phase need not be applied. Consider for example the case when $k = 3$ (see Table 9.4.3). At step 2 of the algorithm we get that the nearest integer

TABLE 9.4.2 Detailed Results for the Goal Chasing Method

Stage (k)	Δ_{k1}^{PTU}	Δ_{k2}^{PTU}	Δ_{k3}^{PTU}	Sequence development	X_{1k}	X_{2k}	X_{3k}	X_{4k}
1	1.1091	1.0149	0.7937*	3-	0	1	1	0
2	0.8485	0.5657*	1.5875	3-2-	1	2	1	1
3	0.8185*	1.4387	0.9327	3-2-1	2	2	2	2
4	1.8655	1.6371	0.2828*	3-2-1-3-	2	3	3	2
5	1.3229	0.8660	0.8660	3-2-1-3-2-	3	4	3	3
6	1.6371	1.8655	0.2828*	3-2-1-3-2-3-	3	5	4	3
7	0.9327	1.2124	0.8185*	3-2-1-3-2-3-3-	3	6	5	3
8	0.5657*	0.8485	1.5875	3-2-1-3-2-3-3-1-	4	6	6	4
9	-	0.7937*	1.0149	3-2-1-3-2-3-3-1-2-	5	7	6	5
10	-	-	0.0000	3-2-1-3-2-3-3-1-2-3	5	8	7	5

point to $V_3 = (0.6\ 0.9\ 1.5)$ is W_k [(1 1 1) or (1 1 2)]. Notice that for the third product, 1 and 2 are equally close to 1.5. If (1 1 1) is chosen, $S_3 = 3 = N_3$, so the routine for this stage ends at step 4. On the other hand, selecting (1, 1, 2) implies that $N_3 - S_3 = 3 - 4 = -1$. Then it proceeds to step 6: Maximum $[1 - 0.6, 1 - 0.9, 2 - 0.5] = 1.5$, which means that w_{33} should be decremented by 1, leading to (1, 1, 1). The algorithm backtracks to step 3, computes S_3 as 3. Now, since $N_3 - S_3 = 3 - 3 = 0$, it stops at step 4. $W_k^* = (1, 1, 1)$.

EDD Heuristic. Using equation (17) we compute the due dates for the second copy of product 1 and the fourth copy of product 3 respectively as

$$\frac{(2 - 1/2)10}{2} = 7.50 \text{ and } \frac{(4 - 1/2)10}{5} = 7.00$$

All others are as shown in Table 9.4.4.

Arranging the product units in increasing order of due dates, we have (product types in brackets) 1.00 (3), 1.67 (2), 2.50 (1), 3.00 (3), 5.00 (2 or 3), 5.00 (3 or 2), 7.0 (3), 7.5 (1), 8.33 (2), and 9.00 (3). This leads to the sequence {3-2-1-3-2-3-3-1-2-3} or {3-2-1-3-3-2-3-1-2-3}.

TABLE 9.4.3 Detailed Results for NIPA

Stage (k)	V_k	$W_k^{\bullet}$	Products scheduled	$\sum_{i=1}^{3} (w_{ki}^{\bullet} - v_{ki}^{\bullet})^2$	Cumulative variation
1	0.20 0.30 0.50	0 0 1	3	0.38	0.38
2	0.40 0.60 1.00	0 1 1	2	0.32	0.70
3	0.60 0.90 1.50	1 1 1	1	0.42	1.12
4	0.80 1.20 2.00	1 1 2	3	0.08	1.20
5	1.00 1.50 2.50	1 1 3	3	0.50	1.70
OR		1 2 2	2	0.50	1.70
6	1.20 1.80 3.00	1 2 3	2 or 3	0.08	1.78
7	1.40 2.10 3.50	1 2 4	3	0.42	2.20
8	1.60 2.40 4.00	2 2 4	1	0.32	2.52
9	1.80 2.70 4.50	2 3 4	2	0.38	2.90
10	2.00 3.00 5.00	2 3 5	3	0.00	2.90

TABLE 9.4.4 Detailed Results for the EDD Heuristic

Product type *i*	*s*th unit (copy) of *i*	Due date
1	1	2.50
	2	7.50
2	1	1.67
	2	5.00
	3	8.33
3	1	1.00
	2	3.00
	3	5.00
	4	7.00
	5	9.00

CONCLUDING REMARKS

The application of the just-in-time concept has proved very useful in reducing inventories, identifying and eliminating wastes, and consequently improving the competitiveness of companies implementing it. Among others, elements such as work standardization, training workers to have multifunction capability, and job security are necessary to derive maximum benefit from it.

Although the models used presently are quite useful, it is rather difficult to quantify the cost benefits in relation to the sequence of products for the final assembly line. Therefore, it would be necessary to have models, which take this into consideration. More would need to be done to address the multicriterion problem. This should include, for example, the development of appropriate weighting schemes for the goals under a multiattribute function framework, as well as other computationally efficient procedures. The application of artificial intelligence techniques including the development and representation of rules to facilitate real-time scheduling would also be useful.

APPENDIX: DYNAMIC PROGRAMMING SOLUTION

Stage	Product *i*	State *Y*	$Y - v_i$	$\gamma(Y - v_i)$	$\mu(Y)$	$\gamma(Y - v_i) + \mu(Y)$	$\gamma(Y)$
0	—	0 0 0	—	—	—	—	0.0000
1	1	1 0 0	0 0 0	0.0000	1.1091	1.1091	1.1091
	2	0 1 0	0 0 0	0.0000	1.0149	1.0149	1.0149
	3*	0 0 1	0 0 0	0.0000	0.7937	0.7937	0.7937
2	1	2 0 0	1 0 0	1.1091	2.2181	3.3272	3.3272
	1	1 1 0	0 1 0	1.0149	1.5875	2.6024	2.6024
	2		1 0 0	1.1091	1.5875	2.6966	
	2	0 2 0	0 1 0	1.0149	2.0298	3.0447	3.0447
	1	1 0 1	0 0 1	0.7937	0.8485	1.6422	1.6422
	2		1 0 0	1.1091	0.8485	1.9576	
	2*	0 1 1	0 0 1	0.7937	0.5657	1.3594	1.3594
	3		0 1 0	1.0149	0.5657	1.5806	
	3	0 0 2	0 0 1	0.7937	1.5875	2.3812	2.3812
3	1	2 1 0	1 1 0	2.6024	2.5436	5.1460	5.1460
	2		2 0 0	3.3272	2.5436	5.8708	
	1	1 2 0	0 2 0	3.0447	2.4228	5.4675	
	2		1 1 0	2.6024	2.4228	5.0252	5.0252

Stage	Product i	State Y	$Y - v_i$	$\gamma(Y - v_i)$	$\mu(Y)$	$\gamma(Y - v_i) + \mu(Y)$	$\gamma(Y)$
	2	0 3 0	0 2 0	3.0447	3.0447	6.0894	6.0894
	1	2 0 1	1 0 1	1.6422	1.8083	3.4505	3.4505
	3		2 0 0	3.3272	1.8083	5.1355	
	1*	1 1 1	0 1 1	1.3594	0.8185	2.1779	2.1779
	2		1 0 1	1.6422	0.8185	2.4607	
	3		1 1 0	2.6024	0.8185	3.4209	
	2	0 2 1	0 1 1	1.3594	1.4387	2.7981	2.7981
	3		0 2 0	3.0447	1.4387	4.4834	
	1	1 0 2	0 0 2	2.3812	1.2124	3.5936	
	3		1 0 1	1.6422	1.2124	2.8546	2.8546
	2	0 1 2	0 0 2	2.3812	0.9327	3.3139	
	3		0 1 1	1.3594	0.9327	2.2921	2.2921
	3	0 0 3	0 0 2	2.3812	2.3812	4.7624	4.7624
4	1	2 2 0	1 2 0	5.0252	3.1749	8.2001	8.2001
	2		2 1 0	5.1460	3.1749	8.3209	
	1	1 3 0	0 3 0	6.0894	3.3586	9.4480	
	2		1 2 0	5.0252	3.3586	8.3838	8.3838
	1	2 1 1	1 1 1	2.1779	1.8655	4.0434	4.0434
	2		2 0 1	3.4505	1.8655	5.3160	
	3		2 1 0	5.1460	1.8655	7.0115	
	1	1 2 1	0 2 1	2.7981	1.6371	4.4352	
	2		1 1 1	2.1779	1.6371	3.8150	3.8150
	3		1 2 0	5.0252	1.6371	6.6623	
4	2	0 3 1	0 2 1	2.7981	2.4249	5.2230	5.2230
	3		0 3 0	6.0894	2.4249	8.5143	
	1	2 0 2	1 0 2	2.8546	1.6971	4.5517	4.5517
	3		2 0 1	3.4505	1.6971	5.1476	
	1	1 1 2	0 1 2	2.2921	0.2828	2.5749	
	2		1 0 2	2.8546	0.2828	3.1374	
	3*		1 1 1	2.1779	0.2828	2.4607	2.4607
	2	0 2 2	0 1 2	2.2921	1.1314	3.4235	3.4235
	3		0 2 1	2.7981	1.1314	3.9295	
	1	1 0 3	0 0 3	4.7624	1.8655	6.6279	
	3		1 0 2	2.8546	1.8655	4.7201	4.7201
	2	0 1 3	0 0 3	4.7624	1.6371	6.3995	
	3		0 1 2	2.2921	1.6371	3.9292	3.9292
	3	0 0 4	0 0 3	4.7624	3.1749	7.9373	7.9373
5	1	2 3 0	1 3 0	8.3838	3.9686	12.3524	
	2		2 2 0	8.2001	3.9686	12.1687	12.1687
	1	2 2 1	1 2 1	3.8150	2.3979	6.2129	6.2129
	2		2 1 1	4.0434	2.3979	6.4413	
	3		2 2 0	8.2001	2.3979	10.5980	
	1	1 3 1	0 3 1	5.2230	2.5981	7.8211	
	2		1 2 1	3.8150	2.5981	6.4131	6.4131
	3		1 3 0	8.3838	2.5981	10.9819	
	1	2 1 2	1 1 2	2.4607	1.3229	3.7836	3.7836
	2		2 0 2	4.5517	1.3229	5.8746	
	3		2 1 1	4.0434	1.3229	5.3663	
	1	1 2 2	0 2 2	3.4235	0.8660	4.2895	
	2(*)		1 1 2	2.4607	0.8660	3.3267	3.3267
	3		1 2 1	3.8150	0.8660	4.6810	
	2	0 3 2	0 2 2	3.4235	1.9365	5.3600	5.3600
	3		0 3 1	5.2230	1.9365	7.1595	

Stage	Product i	State Y	$Y - v_i$	$\gamma(Y - v_i)$	$\mu(Y)$	$\gamma(Y - v_i) + \mu(Y)$	$\gamma(Y)$
	1	2 0 3	1 0 3	4.7201	1.9365	6.6566	
	3		2 0 2	4.5517	1.9365	4.4882	4.4882
	1	1 1 3	0 1 3	3.9292	0.8660	4.7952	
	2		1 0 3	4.7201	0.8660	5.5861	
	3*		1 1 2	2.4607	0.8660	3.3267	3.3267
	2	0 2 3	0 1 3	3.9292	1.3229	5.2521	
	3		0 2 2	3.4235	1.3229	4.7464	4.7464
	1	1 0 4	0 0 4	7.9373	2.5981	10.5354	
	3		1 0 3	4.7201	2.5981	7.3182	7.3182
	2	0 1 4	0 0 4	7.9373	2.3979	10.3352	
	3		0 1 3	3.9292	2.3979	6.3271	6.3271
	3	0 0 5	0 0 4	7.9373	3.9686	11.9059	11.9059
6	1	2 3 1	1 3 1	6.4131	3.1749	9.5880	
	2		2 2 1	6.2129	3.1749	9.3878	9.3878
	3		2 3 0	12.1687	3.1749	15.3436	
	1	2 2 2	1 2 2	3.3267	1.6371	4.9638	4.9638
	2		2 1 2	3.7836	1.6371	5.4207	
	3		2 2 1	6.2129	1.6371	7.8500	
	1	1 3 2	0 3 2	5.3600	1.8655	7.2255	
	2		1 2 2	3.3267	1.8655	5.1922	5.1922
	3		1 3 1	6.4131	1.8655	8.2786	
	1	2 1 3	1 1 3	3.3267	1.1314	4.4581	4.4581
	2		2 0 3	6.4882	1.1314	7.6196	
	3		2 1 2	3.7836	1.1314	4.9150	
	1	1 2 3	0 2 3	4.7464	0.2828	5.0292	
	2*		1 1 3	3.3267	0.2828	3.6095	3.6095
	3(*)		1 2 2	3.3267	0.2828	3.6095	3.6095
	2	0 3 3	0 2 3	4.7464	1.6971	6.4435	6.4435
	3		0 3 2	5.3600	1.6971	7.0571	
	1	2 0 4	1 0 4	7.3182	2.4249	9.7431	
	3		2 0 3	6.4882	2.4249	8.9131	8.9131
	1	1 1 4	0 1 4	6.3271	1.6371	7.9642	
	2		1 0 4	7.3182	1.6371	8.9553	
	3		1 1 3	3.3267	1.6371	4.9638	4.9638
	2	0 2 4	0 1 4	6.3271	1.8655	8.1926	
	3		0 2 3	4.7464	1.8655	6.6119	6.6119
	1	1 0 5	0 0 5	11.9059	3.3586	15.2645	
	3		1 0 4	7.3182	3.3586	10.6768	10.6768
	2	0 1 5	0 0 5	11.9059	3.1749	15.0808	
	3		0 1 4	6.3271	3.1749	9.5020	9.5020
7	1	2 3 2	1 3 2	5.1922	2.3812	7.5734	
	2		2 2 2	4.9638	2.3812	7.3450	7.3450
	3		2 3 1	9.3878	2.3812	11.7690	
	1	2 2 3	1 2 3	3.6095	0.9327	4.5422	4.5422
	2		2 1 3	4.4581	0.9327	5.3908	
	3		2 2 2	4.9638	0.9327	5.8965	
	1	1 3 3	0 3 3	6.4435	1.2124	7.6559	
	2		1 2 3	3.6095	1.2124	4.8219	4.8219
	3		1 3 2	5.1922	1.2124	6.4046	
	1	2 1 4	1 1 4	4.9638	1.4387	6.4025	
	2		2 0 4	8.9131	1.4387	10.3518	
	3		2 1 3	4.4581	1.4387	5.8968	5.8968

Stage	Product i	State Y	$Y - v_i$	$\gamma(Y - v_i)$	$\mu(Y)$	$\gamma(Y - v_i) + \mu(Y)$	$\gamma(Y)$
	1	1 2 4	0 2 4	6.6119	0.8185	7.4304	
	2		1 1 4	4.9638	0.8185	5.7823	
	3		1 2 3	3.6095	0.8185	4.4280	4.4280
7	2	0 3 4	0 2 4	6.6119	1.8083	8.4202	
	3		0 3 3	6.4435	1.8083	8.2518	8.2518
	1	2 0 5	1 0 5	10.6768	3.0447	13.7215	
	3		2 0 4	8.9131	3.0447	11.9578	11.9578
	1	1 1 5	0 1 5	9.5020	2.4228	11.9248	
	2		1 0 5	10.6768	2.4228	13.0996	
	3		1 1 4	4.9638	2.4228	7.3866	7.3866
	2	0 2 5	0 1 5	9.5020	2.5436	12.0456	
	3		0 2 4	6.6119	2.5436	9.1555	9.1555
8	1	2 3 3	1 3 3	4.8219	1.5875	6.4094	
	2		2 2 3	4.5422	1.5875	6.1297	6.1297
	3		2 3 2	7.3450	1.5875	8.9325	
	1*	2 2 4	1 2 4	4.4280	0.5657	4.9937	4.9937
	2		2 1 4	5.8968	0.5657	6.4625	
	3		2 2 3	4.5422	0.5657	5.1079	
	1	1 3 4	0 3 4	8.2518	0.8485	9.1003	
	2		1 2 4	4.4280	0.8485	5.2765	5.2765
	3		1 3 3	4.8219	0.8485	5.6704	
	1	2 1 5	1 1 5	7.3868	2.0298	9.4164	
	2		2 0 5	11.9578	2.0298	13.9876	
	3		2 1 4	5.8968	2.0298	7.9266	7.9266
	1	1 2 5	0 2 5	9.1555	1.5875	10.7430	
	2		1 1 5	7.3866	1.5875	8.9741	
	3		1 2 4	4.4280	1.5875	6.0155	6.0155
	2	0 3 5	0 2 5	9.1555	2.2181	11.3736	
	3		0 3 4	8.2518	2.2181	10.4699	10.4699
9	1	2 3 4	1 3 4	5.2765	0.7937	6.0702	
	2		2 2 4	4.9937	0.7937	5.7874	5.7874
	3		2 3 3	6.1297	0.7937	6.9234	
	1	2 2 5	1 2 5	6.0155	1.0149	7.0304	
	2		2 1 5	7.9266	1.0149	8.9415	
	3		2 2 4	4.9937	1.0149	6.0068	6.0068
	1	1 3 5	0 3 5	10.4699	1.1091	11.5790	
	2		1 2 5	6.0155	1.1091	7.1246	
	3		1 3 4	5.2765	1.1091	6.3856	6.3856
10	1	2 3 5	1 3 5	6.3856	0.0000	6.3856	
	2		2 2 5	6.0086	0.0000	6.0068	
	3*		2 3 4	5.7874	0.0000	5.7874	5.7874

Note: Optimum sequence: 3-2-1-3-2-3-3-1-2-3 or 3-2-1-3-3-2-3-1-2-3
Optimum objective value: 5.7874

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CHAPTER 9.5

PLANNING AND CONTROL OF SERVICE OPERATIONS

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The emerging dominance of the service sector is transforming the U.S. economy and challenging the way we think about productivity, the workplace, and the fairness of the distribution of earnings. In 1960, services accounted for only 39 percent of U.S. gross domestic product (GDP). In 1995, services accounted for 74 percent of U.S. GDP. The growth of service institutions has been phenomenal. All measures point to a continued strong growth. With increased competition and globalization, organizations are being pressured to become more efficient—and lean. They are compelled to plan and control resources effectively. This chapter discusses issues pertaining to planning and control of service operations. Warehousing and distribution is used as a service function example.

INTRODUCTION

The service industry forms the backbone of the U.S. economy. While service institutions are becoming larger and more numerous, their performance is becoming more difficult to control. Scarcely a day goes by without the media decrying the inefficiency of government, the lack of results in public schools, or the poor functioning of transportation systems and software. So, how to make them perform?

Some managers of service organizations tend to run them like a manufacturing business: by applying traditional management techniques to enhance efficiency. But this is only part of the solution. Although a service organization is similar to manufacturing because it has customers to satisfy and certain work to perform, and it must motivate its workers to perform that work, it is very different in its specific mission or purpose. Thus, while some of the tools of manufacturing management can be applied in a service organization, care must be taken to remember the nature of the organization and adapt the tools to fit that nature.

Put in the simplest of terms, services are acts and processes. Relying on the simple, broad definition of services, it quickly becomes apparent that services not only are produced by service businesses but also are integral to the offerings of many manufactured goods producers. For example, car manufacturers offer warranties and repair services for their cars; computer manufacturers offer warranties, maintenance contracts, and training; and industrial equipment producers offer delivery, inventory management, and maintenance services. All of these services are examples of acts and processes.

THE SERVICE SECTOR

Services Defined

Service may be defined as an act that takes place in direct contact between the customer and employees of the service company. Services include all nonmanufacturing organizations except industries such as agriculture, mining, and construction. The U.S. government's Standard Industrial Classification (SIC) system describes service organizations as those primarily engaged in providing a wide variety of services for individuals, business and government establishments, and other organizations. Hotels and other lodging places; establishments providing personal services, repair, and amusement services; health, legal, engineering, and other professional services; educational institutions; membership organizations; and other miscellaneous services are included.

The material gains of a society are achieved by adding value to natural resources. In advanced societies, there are many institutions that extract raw materials, add value through processing them, and transform intermediate material and components into finished products. There are, however, many other institutions that facilitate the production and distribution of goods and add value to our personal lives. The outputs of this latter group are called services.

Services may also be defined as economic activities that produce time, place, form, or psychological utilities. For example, a maid service saves consumers' time spent on household chores. Department stores and grocery stores provide many commodities for sale to consumers in one convenient place. A database service puts together information in a form more usable for the manager. Going to a restaurant may provide psychological refreshment at the end of a busy workweek.

Services can also be defined in contrast to goods. A good is a tangible object that can be created and sold or used later. A service is intangible and oftentimes perishable. It is usually created and consumed simultaneously. Although these definitions may seem straightforward, the distinction between goods and services is not always clear-cut.

In reality, almost all purchases of goods are accompanied by facilitating services, and many services purchased are accompanied by a facilitating good. Thus the key to understanding the difference between goods and services lies in the realization that these items are not completely distinct, but rather are two endpoints on a continuum.

Classification of Service Firms

The range of services provided within a society may be quite broad. Producers of a service may provide the service with no interaction with the consumer beyond the formal sale (vending machine, for example). At the other extreme, the producer of the service may be the consumer, as in the case of the homemaker or a do-it-yourself person who fixes his own appliance or mows her own lawn. In the latter case, there is no economic transaction, so the value of these services do not appear in national data, yet the value is estimated to be quite large.

Most services included in the service sector of the U.S. economy fall between these extremes. The producer and user of the service are distinct, but both participate in providing the service. For example, the lawyer and client work together, the restaurant and customer both contribute to the design of a specific meal and the timing of service, and the school and the student design the student's program and constrain the content and timing of the topics in a single course.

Taking into consideration all of these factors, services may be broadly divided into three main groups:

1. Government (local, state, and federal)
2. Wholesale and retail sales

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3. Other services, like

Business services
Communication
Distribution and warehousing
Financial services
Personal service
Public utilities
Real estate and insurance
Transportation

Characteristics of Services

Through the years, researchers and analysts have used one or more criteria to characterize services. The following is a list of example criteria frequently used to identify services:

- Decentralized facilities are located near the customers.
- High customer contact throughout the service process.
- In general cannot be mass-produced.
- Labor intensive.
- Perishable (i.e., the service cannot be stored in inventory, but is consumed in production).
- Pricing options are usually more elaborate.
- Quality control is primarily limited to process control.

Differences and Similarities with the Manufacturing Sector

The managers of today's businesses are applying basic concepts of quality, process analysis, job design, facility location, capacity planning, layout, inventory, and scheduling to both manufacturing and the provision of services. The benefits are improved quality, reduced costs, and increased value to the customers, all of which give the firm a competitive edge.

Differences. The differences between manufacturing and service organizations fall into the eight categories shown in Fig. 9.5.1. However, these distinctions actually represent the ends of a continuum. The first distinction arises from the physical nature of the product. Manufactured goods are physical, durable products. Services are intangible, perishable products—often being ideas, concepts, or information.

The second distinction is with regard to the output. Manufactured goods are outputs that can be produced, stored, and transported in anticipation of future demand. Creating invento-

More like a manufacturing organization	Hybrid	More like a service organization
1. Physical, durable product		Intangible, perishable product
2. Output can be inventoried		Output cannot be inventoried
3. Low customer contact		High customer contact
4. Long response time		Short response time
5. Regional, national, or international markets		Local markets
6. Large facilities		Smaller facilities
7. Capital intensive		Labor intensive
8. Quality easily measured		Quality not easily measured

FIGURE 9.5.1 Differences between manufacturing and service businesses.

ries allows managers to cope with peaks and valleys in demand by smoothing output levels. By contrast, services cannot be preproduced. Without inventories as a cushion against erratic demand, service organizations are more constrained by time and usually have a need for variable staffing. A third distinction is customer contact. Most customers for manufactured products have little or no contact with the production system. Primary customer contact is left to distributors and retailers. In many service organizations the customers themselves are inputs and active participants in the process. Some service operations have low customer contact at one level of the organization and high customer contact at other levels. For example, the branch offices of parcel delivery, banking, and insurance organizations deal with customers daily, but their central offices have little or no direct customer contact. Similarly, the back room operation of a jewelry store has little customer contact, whereas sales counter operations involve a high degree of contact.

A related distinction is response time to customer demand. Manufacturers generally have days or weeks to meet customer demand, but many services must be offered within minutes of customer arrival. The purchaser of a computer may be willing to wait several weeks for delivery. In contrast, a grocery store customer may grow impatient after waiting five minutes in a checkout lane. Because customers for services usually arrive at times of their choosing, service operations may have difficulty matching capacity with demand. Furthermore, arrival patterns may fluctuate daily or even hourly, creating even more short-term demand uncertainty.

Two other distinctions concern the location and size of an operation. Manufacturing facilities often serve regional, national, or even international markets and therefore generally require larger facilities, more automation, and greater capital investment than service facilities do. In general, services cannot be shipped to distant locations. For example, a hairstylist in Cincinnati cannot give a haircut to someone in Seattle. Services require direct customer contact, and consequently must locate relatively near their customers.

A final distinction is the measurement of quality. Because manufacturing systems tend to have tangible products and less customer contact, quality is relatively easy to measure. The quality of service systems, which generally produce intangibles, is harder to measure. Moreover, individual preferences affect assessments of service quality, making objective measurement difficult. For example, one customer might value a friendly chat with the salesclerk during a purchase, whereas another might assess quality by the speed and efficiency of the transaction.

Similarities. Despite having so many differences, the similarities between manufacturing and services are numerous. Every organization has processes that must be designed and managed effectively. Some type of technology, be it manual or computerized, must be used in each process. Every organization is equally concerned about quality, productivity, and the timely response to customer demand. A service organization, like any manufacturer, must make choices about the capacity, location, and layout of its facilities. Every organization deals with suppliers of outside services and materials, as well as scheduling problems. Matching staffing levels and capacities with actual demands is a common problem.

The distinction between manufacturing and service organizations can get cloudy. Manufacturers do not just offer products, and service organizations do not just offer services. Many organizations normally provide a package of goods and services. Customers expect both good service and good food at a restaurant and both good service and quality goods from a retailer. Manufacturing firms offer many customer services, and a decreasing proportion of the value added by the services directly involves the transformation of materials.

Despite the fact that service organizations cannot inventory their outputs, they must inventory the inputs for their products. These inputs must undergo further transformations during provision of the service. Hospitals, for example, must maintain an adequate supply of medications. As a result, wholesale and retail firms typically hold over 40 percent of the U.S. economy's inventory. In addition, manufacturing firms that make customized products or limited-shelf-life products cannot inventory their outputs.

Although there is high customer contact in service organizations, relative to that of manufacturing firms, still there are operations in services that have little customer contact, such as the back room operations of a bank or the baggage-handling area at an airport. Moreover, as they seek ways to improve quality, both manufacturing and service firms are beginning to realize that everyone in an organization has customers—outside customers or inside customers in the next office, shop, or department who rely on their inputs. A strong customer focus is needed when managing operations, whether in services or in manufacturing.

Impact on U.S. Economy

While many modern-day economies are dominated by services, the United States and other countries did not become service economies overnight. According to the Bureau of Labor Statistics, as early as 1929, about 55 percent of the working population was employed in the service sector in the United States, and approximately 54 percent of the gross national product was generated by services in 1948. The trend toward services continued, and by the mid-1990s services represented almost 73 percent of the gross domestic product and 79 percent of employment. Manufacturing and other goods-producing industries accounted for the remaining 21 percent of jobs in the United States.

While the growth in services is remarkable, not all service industries have grown at the same rate. A disproportionate amount of the growth in employment has come from producer services such as legal, accounting, engineering, and government. In some service industries, such as retail, the percentage of total employment they represent has remained relatively flat, whereas in others, such as wholesale or distribution services, employment has actually fallen.

NEED FOR PLANNING AND CONTROL IN SERVICE OPERATIONS

Many aspects of services are identical to manufacturing. The planning and control process for services is often the same as for manufacturing. The major goals of service planning and control are to

- Satisfy customer needs and expectations
- Produce required services efficiently
- Maintain acceptable quality as seen by the customer

The need for planning and control in service operations can be better explained based on the type of product or service involved, the level of automation, and forecasts of future demand.

Product Versus Nonproduct

The planning and control operations must consider what product(s) or service(s) will be produced. Product-related information is often developed from the marketing plan or the corporate master plan. The number of products or services and the range of the product or service lines is constrained by the business environment. For example, airlines and trains provide two or three levels of service (nonproduct), sometimes called regular or coach fare, business class, and first class. A refrigerator manufacturer might build several models (product) and market them regionally, nationally, or internationally.

Level of Automation

Advanced technology is rapidly becoming an important aspect of service organizations. One popular example in the service sector is the fast food industry, which for several years has developed automation to increase quality and productivity as well as to respond to growing labor shortages. For example, some years ago PepsiCo, Inc. tested a fully automated soft drink system. In their system, orders were keyed in at the cash register and were transmitted to a computer in the dispenser. Under computer control, the dispenser drops a cup, fills it with ice and the soft drink, and puts a lid on it. The drink is then moved by conveyor to the server. The system was designed to let workers interact more with the customer rather than spending time filling drinks.

Forecasting

Forecasting demand for services is just as important as forecasting product demand in manufacturing firms, especially when heavy capital investment is needed to provide the service. For example, airlines need forecasts of demand for air travel to plan for purchases of aircraft. The travel and tourism industry makes seasonal forecasts of demand, university administrators require enrollment forecasts, city planners need forecasts of population trends to plan highways and mass transit systems, and restaurants need forecasts to be able to plan for food purchases and server personnel.

Service organizations have some unique characteristics that impact forecasting. For instance, the customer demand for many services in the airline and hotel industries is highly seasonal. Demand for services may also vary with the day of the week or time of the day. Grocery stores, banks, and similar businesses need very short-term forecasts to plan for variations in demand. Forecast information is needed for work-shift scheduling, vehicle routing, and other operating decisions.

Benefits of Planning and Control

Planning assists management in defining and anticipating the future environment and developing appropriate alternatives. It also allows management to operate more effectively by reacting rapidly and accurately to changing environments.

Customer satisfaction is one of the major results of planning and control. This is because better control over materials and human resources can lead to lower costs passed on to customers in lower prices. As another example, a health care provider that practices strategic planning will be able to offer better policies. This is because they will be able to plan or forecast changes in medical technology. However, the key to providing customer satisfaction in any service business is to balance customer expectations with the quality and value of a given service. Moreover, utilizing planning and control tends to make an organization more proactive or customer oriented rather than reactive.

WAREHOUSING AND DISTRIBUTION—A SERVICE FUNCTION EXAMPLE

Introduction

Traditionally, industrial engineering practice tended to concentrate on the manufacturing process, costing on average about one-half the selling price of the goods. With the emergence of the service sector, industrial engineering techniques have played an increasing role in the service segment of this total cost framework. An example of these activities involves the warehousing of products and their delivery to the customer. The customer could be another company or plant, a wholesale distributor, a retailer, or the consumer.

Storage and warehousing operations are a critical part of a profitable business. With increasing competition and tremendous pressures on operating margins, the necessity for a sophisticated warehousing management system has become indispensable. There are nearly 300,000 warehouses spread across the length and breadth of the United States employing nearly 2.5 million people with the cost of warehousing being nearly 5 percent of the gross national product. The traditional school of thought had concluded that warehousing did not add any value to the product and that it was purely a cost-adding activity. However, the true value of warehousing lies in having the right product in the right place at the right time—serving the customer. Without a complete and accurate understanding of the value of warehousing, companies have paid dearly. Warehouse planning must be constantly scrutinized and must be tailored to meet anticipated future requirements. The functions performed by a warehouse can be defined as follows:

- Receiving the goods from a source
- Storing and keeping track of the goods
- Picking the goods when they are required
- Shipping the goods to the appropriate customer

Requirement and Strategies for Successful Warehousing

Without a complete and accurate understanding of the value of warehousing, many companies have failed to give warehousing the same scientific scrutiny as the other aspects of their business. To be successful, warehouse planning and control must be accomplished within the framework of a clear, long-term vision of where the operations are headed. A successful warehouse operation typically follows the strategies outlined here:

- Warehousing must be viewed as a critical step in the material flow and not as a necessary evil.
- Warehouse operations must be aware of the customer's requirements and consistently meet those requirements.
- Warehouse standards must be established, performance must be measured against standards, and timely actions must be taken to overcome any deviations.
- Systems must be put in place and must be conducive for proactive decisions.
- The trend is toward larger, centralized warehouses instead of smaller, decentralized warehouses.
- Warehouses need to be flexible—allowing for multiple uses.
- Activities within the warehouse must be more integrated into the overall material flow cycle.
- Cycle counting must be used to manage inventory accuracy, and accuracy above 95 percent must be the norm.
- Procedures and layouts must be designed to maximize picking efficiency and effectiveness in terms of correct ergonomic design and safety considerations.
- Vendors, customers, and a wide variety of functions within the warehouse must be integrated into a single service-providing activity.
- Advanced technologies must be more easily embraced and economically justified.
- All warehouse operations should be conducted to ensure conformance to customer requirements.
- Automatic identification systems must be the norm for data acquisition and transfer.
- Real-time, paperless control systems must be used throughout modern warehouses.

Warehouse Objectives

The resources of a warehouse are space, equipment, and personnel. The cost of space not only includes the cost of building or leasing space but also the cost of maintaining and operating the space. The equipment resources of a warehouse include computers, dock equipment, loading and material-handling equipment, and storage equipment, all of which combine to represent a sizable capital investment in the warehouse. The following objectives must be met for a warehouse to be successful:

- Maximize effective use of space.
- Maximize effective use of equipment.
- Maximize effective use of labor.
- Maximize accessibility of all items.
- Maximize protection of all items and employees.

Work Measurement Techniques for Warehousing Operations

This section defines the various work measurement techniques being used for performance measurement in a typical service activity like warehousing and distribution. One of the problems faced by warehouse managers is the effective use of personnel. Good management means knowing what can be expected from employees, and that requires establishing performance standards. Such standards are needed to determine

- Labor content of the service performed
- Staffing needs of the organization
- Cost and time estimates prior to performing services
- Productivity expectations
- Wage incentive plans
- Efficiency of employees

Properly set standards represent the amount of time it should take an average employee to perform the specific job activities under normal working conditions. Similar to the manufacturing sector, labor standards in the service sector are established by using traditional work measurement techniques. The following five categories of work measurement techniques are used in the service sector:

1. Predetermined time systems
2. Direct observation timing with performance rating (stopwatch time study)
3. Work sampling
4. Historical data (includes accounting records and self-logging)
5. Judgment estimating

The first three are considered engineered work measurement techniques. The last two, historical data and judgment estimating, are often used to approximate standard time values. However, these techniques have decreased accuracy and little underlying theory or standardized procedures and consequently are not considered engineered work measurement practice. Additional techniques, such as standard data and mathematical modeling, are also useful in the establishment of service industry work standards. The engineer must be aware of the accuracy required for a given standard or other work measurement application when using any of these techniques.

To varying degrees, these five techniques may be used for the measurement of service work, depending primarily on accuracy requirements but also considering availability of human resources, time to determine the standard, and management objectives. It is important to know the strengths and limitations of each technique. This is useful in technique selection when evaluating the cost of establishing standards versus the cost of having inaccurate or no production standards.

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There are customized work measurement techniques such as specialized predetermined time systems for specific applications. For example, AutoMOST has been used to automatically determine performance standards from a specific set of variables for the order-filling functions in warehousing operations.

Implementation of a Work Measurement System

The implementation and maintenance of a successful work measurement program can be defined as bringing such a program into practical application and ensuring that the program meet its objective by providing a realistic measure of how much time should be required to perform a defined quantity of work. The advantages of a work measurement program include the following:

- Capital equipment investment justification
- Compensation and incentive payment
- Credible service cost
- Effective organization size and structure
- Labor requirements and unit labor cost
- Planning, control, and budgeting
- Service pricing
- Quality attainment and monitoring
- Scheduling of both labor and material movement
- Work design and human factors considerations

Implementation activities should be designed according to the following recommendations:

- The purpose for having a work measurement program must be defined.
- Continuous communication and persuasion should be practiced to avoid or minimize resistance to the program.
- All the work measurement techniques should be performed by trained analysts.
- Continuous follow-up meetings should be maintained throughout implementation.
- Train all individuals involved in the process.
- The contribution of ideas, techniques, and better approaches should be readily welcomed and acknowledged at all times.
- Select an area that can be easily and successfully installed early in the total implementation program.
- Embed a good reporting system that can be readily understood by all levels in the organization, with the results being made available to the workers as well as management.
- Trial runs should be scheduled along with the training activities to serve as a learning process for the analysts, workers, and supervisors.
- Refrain from disbanding the old system completely before all the defects are eliminated in the new system.

RESOURCE PLANNING TO SATISFY DEMAND

Resource planning is the process of determining the types and amounts of resources that are required to implement an organization's plan. The goal of resource planning in a typical service facility like warehousing and distribution is to determine the appropriate level of service capacity—as represented by facilities/space, equipment, and labor—that is required to meet future service demand.

Capacity Planning

Capacity planning strategies at a typical warehouse involve an assessment of existing capacity, forecasts of future capacity requirements, a choice of alternative ways to build capacity, and a financial evaluation. In developing a long-range capacity plan, a firm must make a basic economic trade-off between the cost of capacity and the opportunity cost of not having adequate capacity. Capacity cost includes both the initial investment in facilities and the annual cost of operating and maintaining the facilities.

Output measures of capacity for service production are more difficult to interpret and control, since the rate at which humans work is more variable than that of machines. Therefore, input measures are more commonly used. Service organizations should forecast the human effort involved in providing necessary services.

Storage Space Planning

Space planning is the part of the science of warehousing concerned with making quantitative assessment of warehouse space requirements. Space planning consists of the following general steps:

1. Determine what materials are to be stored.
2. Determine the storage philosophy.
3. Determine space allowances for each element required to accomplish the activity.
4. Calculate the total space requirements.

The first two steps of the space planning process define the activity, techniques, equipment, information, and so on to be used in performing that activity. Once the maximum inventory levels have been determined, the inventory level that will be used as a basis for planning required storage space must be calculated. There are two major material storage philosophies: fixed (or assigned) location storage and random (or floating) location storage. In fixed location storage, each individual stock-keeping unit will always be stored in a specific storage location. No other stock-keeping unit may be assigned to that location even though the location may be empty. With random location storage any stock-keeping unit may be assigned to any available storage location. The amount of space planned depends on the method of assigning space. If fixed location storage is used, then sufficient space must be assigned to store the maximum amount of stock-keeping units that will ever need to be stored at any time. For a random location storage unit, the maximum amount of items on hand at any time will be the average amount of each stock-keeping unit. Usually the storage philosophy for a specific stock-keeping unit will not be strictly fixed, and during most of the time, the storage philosophy might be a hybrid of the two.

Each of the discussed storage philosophies has its own merits and limitations. Space utilization is poor in a fixed location system, while it is far better in a random storage system. However, accessibility of material stored in a fixed storage system is better because the location of a particular product is always known. Accessibility to material in random storage systems depends on a good material locator system. The material locator system keeps track of the present location of every item in storage. In both fixed and random storage location systems, the flow of material is straightforward and economical. The third step involves determining the space requirements of each element that contributes to performing the activity. In warehousing, these elements commonly include personnel services, material handling and material storage requirements, and maintenance services and utilities. Finally, step four combines the space requirements of the individual elements to obtain total space requirements.

Storage space planning is particularly critical because the storage activity accounts for the bulk of the space requirements of a warehouse. Inadequate storage space planning can easily result in a warehouse that is significantly larger or smaller than required. Too little storage space can result in a horde of operational problems like lost stock, inaccessible material, safety problems, and low productivity. Too much storage space will result in poor use of resources and high space costs in the form of land, equipment, and capital.

Labor and Equipment Planning

For a firm that employs a large number of service providers, labor or staffing levels and equipment can be the primary capacity constraint. A warehouse and distribution operation, being very labor and equipment intensive, may face the reality that at certain times demand for their organization's services cannot be met because the staff or equipment is already operating at peak capacity. However, it does not always make sense to hire additional service providers if low demand is a reality at other times. In this situation, the firm should attempt to hire part-time workers during high demand times.

CONCLUSIONS

It is important to understand the characteristics of the service business (e.g., level of automation, product versus nonproduct, and ability to forecast service demand) before developing a planning and control system. Warehousing and distribution provides an example of a service function with specific characteristics that impact the planning and control system.

Work measurement and performance standards are an important aspect of management planning and control in service firms. Measurements establish baselines and trends. They also identify problem situations that must be addressed and resolved. The process of measurement provides information for decision making concerning capacity planning and staffing, and establishes priorities for action. In this way, control is extended and planned goals can be achieved.

The measurement system should be designed early in the planning stage, rather than as an afterthought. Incorporate the economics of collecting, reporting, and maintaining measurements in the design. Good measurements and performance standards lead to good outcomes and serve as an essential link between planning and control.

FURTHER READING

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PLANNING AND CONTROL OF SERVICE OPERATIONS

BIOGRAPHY

Richard L. Shell, Ph.D., P.E., is professor of industrial engineering in the College of Engineering and is professor of environmental health in the College of Medicine at the University of Cincinnati. His specialization areas include ergonomics/safety engineering, human performance, incentive motivation, and manufacturing. He received the Institute of Industrial Engineers Fellow Award in 1988, and was elected a fellow of the Society of Manufacturing Engineers in 1995. His most recent book, *Time Based Manufacturing,* was coauthored with Joe Bockerstette and copublished by Industrial Engineering and Management Press and McGraw-Hill.

Source: MAYNARD'S INDUSTRIAL ENGINEERING HANDBOOK

CHAPTER 9.6

DEMAND FLOW® TECHNOLOGY (DFT)

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This chapter discusses Demand Flow® technology (DFT), the mathematically based technology whereby work is defined using linear and Takt techniques to design mixed-model flow lines and processes.* Response and flexibility have emerged as the key differentiators for manufacturing in the late twentieth century. Customers demand product availability and flexible order policies. With DFT methodology, manufacturers no longer use MRP systems to schedule fabricated items and subassemblies, nor do they issue material based on production work orders. In the flow environment, products are built in work content time, not traditional lead time. The end result is an ongoing sequence of product in a flow process that replenishes from other internal processes and external suppliers based on actual customer demand. Companies can respond quickly to changing customer demands and can leverage Demand Flow technology as the weapon established in manufacturing to gain market share and optimize margins.

BACKGROUND

Demand Flow Technology as a Competitive Advantage

Today, manufacturers understand that their customers are unwilling to wait for product availability. In order to meet these market requirements, many manufacturers have resorted to carrying large finished-goods inventories. Unfortunately, even massive finished-goods inventory investments are based on forecasted demand. Therefore, an educated guess is made regarding the specific models that consumers will buy. Even the best guess will always be inaccurate, thus leaving unfulfilled customer orders. In addition to the negative impact to customer delivery performance, a strategy of holding extensive finished-goods inventory to satisfy customer demand is extremely expensive. These finished goods are burdened with labor and overhead and are vulnerable to obsolescence as well as to damage and loss. Because most manufacturers use the existing techniques of MRP, MRPII, scheduling, routing, and so forth, their manufacturing lead times exceed their customer-quoted lead times. Manufacturers therefore are forced to forecast their requirements and hope that their customer orders match that expectation. The outdated techniques of schedule-based functional manufacturing are no longer competitive. The proven tools of the mathematically based Demand Flow technology (DFT) provide a viable alternative.

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*Demand Flow® is a registered trademark of the John Costanza Institute of Technology, Inc. (JCIT).

DEMAND FLOW MANUFACTURING

Demand Flow manufacturing is a pull process, pulled from the back, or the completion, of the product. The pull begins at the very end of the production flow process and continues forward through the flow, through feeder processes and machine cells, to the point-of-usage inventories and eventually even to suppliers. Parts are pulled into and through the process by a demand that is established at the end. The daily rate is achieved at the end of the flow process as opposed to the scheduling and lead-time techniques of traditional manufacturing. Product synchronization is a technique to show the relationship of the individual flow processes coming together to create the part or product. Thus, the flow process may resemble an inverse tree with individual processes, with assembly or machine cell branches feeding into the main flow at the points at which their components are needed. (See Fig. 9.6.1.)

Total Quality Control (TQC)

Once the product synchronization is defined, each of the individual processes is broken into a TQC sequence of events (SOE). TQC is the total quality control technique in Demand Flow manufacturing that brings quality into the manufacturing process at the point where work is being performed. TQC is defined by the sequence of events, and it occurs at every step in the production process. Since the end of the process is given the highest priority for implementation, final assembly processes are targeted for starting points in defining the TQC sequence of events.

DEMAND FLOW MANUFACTURING DATA ELEMENTS

The new terminology of flow manufacturing has been developed and refined to ensure consistency. The DFT manufacturer will communicate with terms such as *synchronization, sequence of events, total product cycle time, raw-in-process inventory (RIP), flexible windows, flow-based costing, operations cycle time,* and many others. Demand Flow technology is based on a production flow process that uses kanbans to pull material into and through the process as the material is consumed. Material is pulled from a nearby point of supply into the rate-based production flow process. It is a flexible pull system that views a product as a pile of parts that is pulled through a sequence of events where work is performed by people or machines to create the product. The underlying objective of DFT is to produce the highest-quality product in a customer-responsive flow process.

The TQC sequence of events is the first key element of a TQC flow process, illustrated in Fig. 9.6.2. It is the series of work content steps and quality criteria that need to be completed in order to manufacture the quality product. When doing a TQC sequence of events, there is a natural tendency for traditional batch manufacturers to think in terms of batches, lumps, or traditional subassemblies, the thought process should follow the natural flow of the product.

The TQC sequence of events is a natural flow of the tasks required to create a product. The sequence of events describes the sequential work and, most important, the quality criteria for each work step to manufacture the product. Each task in the sequence of events is classified in one of the following four categories of work:

1. Required labor work
2. Required machine work
3. Setup time
4. Move time

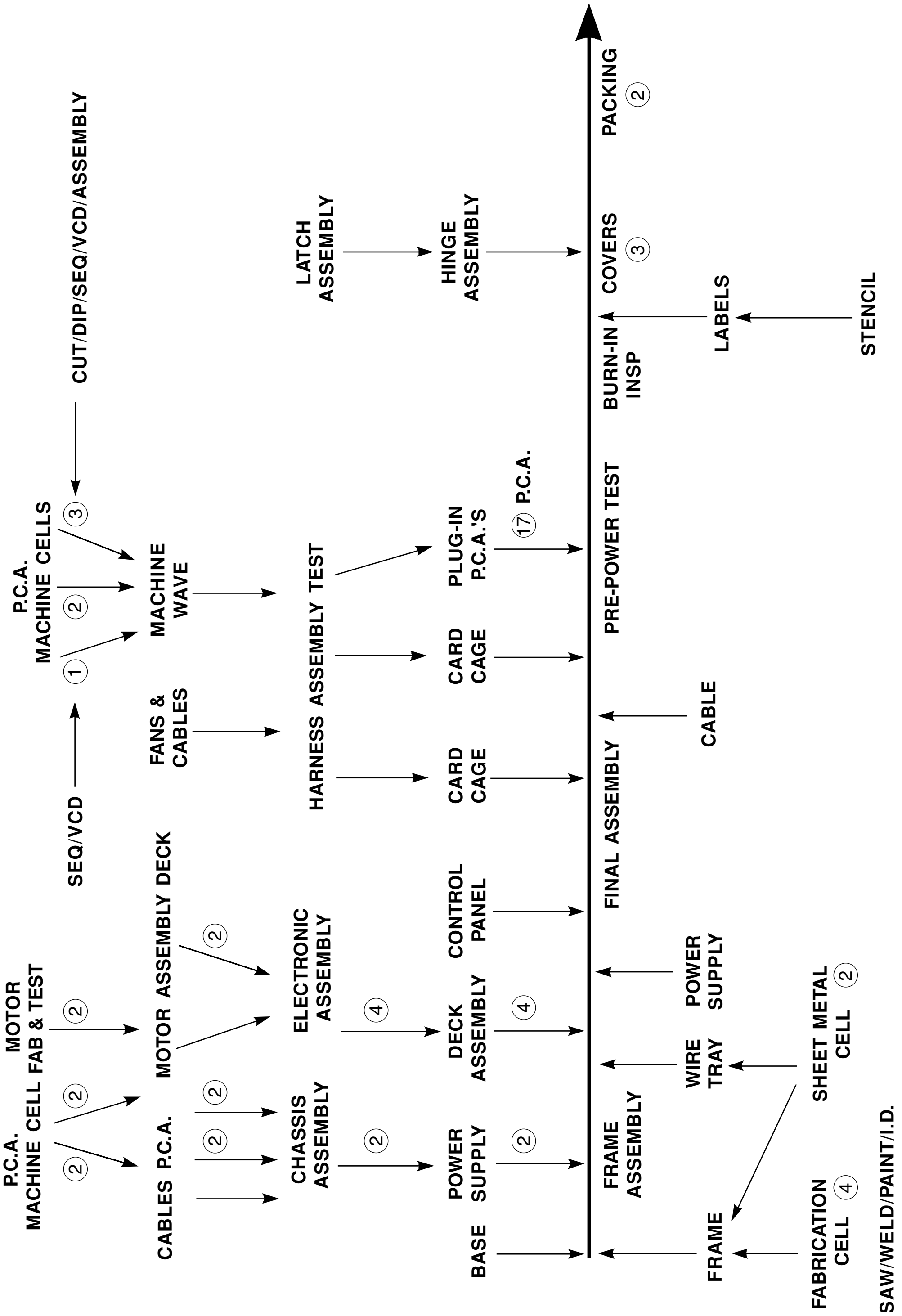

P.C.A. MACHINE CELL
MOTOR FAB & TEST
SEQ/VCD
P.C.A. MACHINE CELLS
CUT/DIP/SEQ/VCD/ASSEMBLY
①
②
③
CABLES
P.C.A.
MOTOR ASSEMBLY DECK
FANS & CABLES
MACHINE WAVE
CHASSIS ASSEMBLY
ELECTRONIC ASSEMBLY
HARNESS ASSEMBLY TEST
LATCH ASSEMBLY
BASE
POWER SUPPLY
DECK ASSEMBLY
CONTROL PANEL
CARD CAGE
CARD CAGE
PLUG-IN P.C.A.'S
⑰ P.C.A.
HINGE ASSEMBLY
FRAME ASSEMBLY
FINAL ASSEMBLY
PRE-POWER TEST
BURN-IN INSP
COVERS ③
PACKING ②
FRAME
WIRE TRAY
POWER SUPPLY
CABLE
LABELS
FABRICATION CELL ④
SHEET METAL CELL ②
STENCIL
SAW/WELD/PAINT/I.D.
②
④

FIGURE 9.6.1 Product synchronization.

PRODUCT P/N MODEL 100	DEMAND FLOW® TECHNOLOGY								PROCESS I.D. MOTOR
SEQ.	TASK DESCRIPTION	V.A.	SET-UP		MACHINE	LABOR	MOVE		TQC INFORMATION
			M	L			M	L	
7.0	Remove shim			0.10					
7.1	Remove second shim			0.10					
8.0	Remove armature cover (PN 752) from plastic bag			0.10					
9.0	Install armature cover over guide pins to armature base	*		0.15		0.10			Verify proper orientation
10.0	Remove guide pin			0.15					
10.1	Remove second guide pin	*				0.30			Torque to hand tight only
11.0	Attach armature cover to armature base with 8-	*							

FIGURE 9.6.2 DFT/TQC sequence of events.

The quality requirements for each step are then identified. The primary objective—to produce the highest-quality product via TQC—cannot be achieved until the manufacturer understands the specific work and the corresponding quality requirements essential to produce a product. Above all, the manufacturer must commit to taking quality to the people and machines that build the product. The path to total quality products is based on the foundation of a total quality process.

Dominant global manufacturing is based on a flow process in which the people and machines that build the product are given the involvement, responsibility, TQC tools, authority, and methods to achieve their goal. Outdated and expensive external quality inspection techniques, although still practiced by many companies in the defense industry as well as in some other government-regulated industries, focus on external inspection tools and final product tests. Those antiquated practices ("We've always done it this way" or "We're unique") seem preferred over creating a process that eliminates the initial opportunity to create a nonquality part or product. The responsibility of quality must start in design engineering and become a predominant focus at each step to build a product. Once the sequence of events has been developed and the quality criteria defined, this flow of the product will then dictate the line layout. The associated work content time will also assist management in determining the number of machines and people required to produce the forecasted volumes of products.

Every step to manufacture a product will be associated with one of the four categories of work. Work will be classified to ensure that the requirements for meeting product specification are understood and met and to prioritize improvement to the process. All steps to build a product will fall into one of those four categories of work. However, not all work will add value to the product or process, even though it must be completed in order for the customer's expectations and product specifications to be met.

Each step is also classified as a value- or non-value-added step. Value-added steps in the production process are those that increase the worth of a product or service to a customer or consumer. Value-added steps can be determined only by viewing the product from the customer's standpoint. It is essential to differentiate value-added steps from steps that do not add value so that efforts can be made to increase the percentage of value-added steps and, wherever possible, to eliminate steps that do not add value. Sometimes that is not possible. As an example, in-process testing that is not required in your product specification is not value-added. The testing-time work would fall under the setup time classification. Testing would be value-added if the customer required it to be part of your product's specification. The product needs to perform and provide dependable service to the customer, and testing is a way to prevent process and material defects from getting to the customer—but the testing itself does not add value.

Required labor time represents those employee-performed steps that are necessary for the product to meet your advertised product specifications. While labor time is needed in order for the product to meet these specifications, not all labor time is value-added.

Likewise, required machine time represents the machine-performed steps essential for the product to meet your specifications. Required machine time, like required labor time, may or may not add value to the product.

Move time is the time spent in moving products or materials through the process, from the point where they were produced or introduced to the point where they will be consumed. Move time may be related to either labor or machine time. It is always non-value-added work. Appreciable move time is usually indicative of a poor line layout.

Setup time is work that is performed prior to required machine or labor time, and it, too, is always non-value-added. Setup time can range from changing a tool pack and making the necessary adjustments on a large machine to opening and removing a cable from a package. Once the non-value-added step is identified, modifications in packaging, line layout, and machine setup procedures can often be made to reduce setup time.

Sequence of Events Versus Routing

The TQC sequence of events is quite different from a traditional product routing. The traditional product routing tends to be of a summary nature and typically includes operations for assembly, inspection, testing, setup time, move time, and run time for both machine and labor. The traditional routing is useful in routing the product from work center to work center and in loading the planned hours in each traditional department or work center. The labor routing does not distinguish between a value- and non-value-added step. Thus, in conventional manufacturing there is no effective way to determine which steps should be targeted for elimination. The traditional router is used as a collection device to gather employee efficiency data or process performance data based on the work order that has been scheduled. Most important, the traditional router does not contain the specific verification or TQC criteria essential to a total quality process. Typically, a traditional router will direct the product or subassembly to go to inspection to be approved by an external inspector.

The TQC sequence of events in the flow process is a key element in the design of the fundamental flow process. It will be used as a basis to methodize the process; it will be used for total product cycle time calculation; and it will point the way to process improvement via the identification of dangerous designed-for-defect steps and the elimination of non-value-added steps. Standard routings have little value in flow manufacturing and should not be used if a scheduling manufacturer is transitioning to Demand Flow technology. Compromises on establishing the quality flow process will affect the success of the overall project. Such compromise is often tied to a lack of understanding or commitment from the top management.

Once the TQC sequence of events has been defined, the total time to build the product can be calculated. The sum of all machine, labor, setup, and move sequences will be the total time to build the product. The total time to build the product is usually broken into total labor time and total machine time. This labor and machine time will be used to determine staffing and machine utilization in the manufacturing plant based on the daily rate to be achieved. Adding together all work content, value- and non-value-added, to build or machine a product will reveal the total labor and total machine time needed to create the product.

All of the value-added steps are required if the product is to meet customer expectations and manufacturer's specifications. It is natural to place all value-added steps in a cost category that charges them directly to product costs. The non-value-added steps are placed into a cost category regarding ineffective manufacturing costs. These ineffective product costs are not dictated by the customer requirements or product specification. These non-value-added steps contribute to higher product costs and lower profit margins. The relation of value-added time versus total time yields the following process efficiency formula:

$$\text{Process design efficiency } \% = \frac{\text{VW}}{\text{TT}} \times 100$$

where

TT = total labor time + total machine time (V+ NV)
VW = sum of the value-added work content (machine and labor) time
NV = sum of the non-value-added work content (machine and labor) time

Management attention is focused on the elimination of non-value-added steps and the improvement of the process quality. As non-value-added steps are removed or reduced, the manufacturing process efficiency will increase.

Demand Flow Technology Line Design Calculations

Through the TQC sequence of events, we have identified the total work and total quality criteria to build a product. Once this is completed, the work content would ideally be grouped into equal pieces of work as we start designing a flow process. Under ideal conditions, each piece would require exactly the same length of work content time. An ideal layout of the entire production process, including the line, feeders, and machine cells, would hopefully show each process cut into equal pieces of work content time. If it took a total of 16 hours to create a product, and such production was achieved by 32 increments of 30 minutes each, the pull process of flow manufacturing would function smoothly, perhaps perfectly, completing a product every 30 minutes.

However, since most processes are dominated by nonperfect people and dissimilar machines, an absolute synchronization cannot be achieved. Therefore, a series of balancing techniques has been developed for flow manufacturing. These techniques have the effect of equalizing the pieces of work. They enable shaping the relationship of processes and coordinating the elements of work content. *Operational cycle time,* the takt of the process, and *flow balancing techniques,* which drive the design of the entire process, are two of those techniques. *Takt,* a German word for rhythm or beat, is used in the Demand Flow process to define the targeted work content for people and machines to meet the production capacity that the Demand Flow line was designed to achieve. All processes on the dedicated product synchronization or mixed-model process map may have different takt times if they have different volumes or yields. Mathematically, takt time is always defined by the operational cycle time calculation.

Designed daily rate (capacity) and the corresponding flow targets must be established for each product to be manufactured. This targeted rate at capacity is based on a marketing and top-management agreement. Normally, flow lines are designed, one time, at the highest required rate (capacity). Usually, that is a volume that cannot be surpassed unless a second or third shift is utilized or unless the workweek is stretched from five to six or seven days. Although they are designed at one volume, which is capacity, flow manufacturing lines are flexible and can easily run well below that volume. Based on actual demand and without redesigning the line or changing a single production method sheet, the range of volumes produced will be between the designed maximum volume and 50 percent of that volume. To calculate the designed daily rate, divide the targeted monthly volume by the number of workdays in the month:

$$\text{Dcp} = \frac{\text{Pv}}{\text{Wd}}$$

where Dcp = designed daily rate (capacity)
Pv = targeted monthly volume
Wd = work days per month

This will provide the targeted number of units to be produced per day as the designed daily rate. As an example, if the designed monthly plan is based on 500 units and the total number of workdays per month is 20, the designed daily rate would be 25 units per day. Although the daily rate can and will be adjusted a little every day, flow lines are designed one time at the capacity volume.

Flow rates are tools used in the design as well as in the daily management of a flow process. They are based on actual daily units completed at the back of the flow process. In the flow rate calculation, the use of effective work hours, or the amount of time that can be anticipated as actual work time, is required. As a typical example, production employees work a standard 8½-hour day, with allowances for a 30-minute lunch and two 15-minute breaks. The remaining work time is then factored down between 12 and 18 minutes a day to allow for quality discussions and personal time. Based on this example, the effective work hours would be 7.3. The flow-line flow rate is equal to the specific daily rate divided by the effective work hours times the number of shifts per day:

$$\mathrm{Fr} = \frac{\mathrm{Dr}}{\mathrm{H(S)}}$$

where Fr = daily flow rate
Dr = daily rate
H = effective work hours
S = work shifts per day

Thus, a daily rate of 50 units divided by 7.3 hours in a one-shift operation would yield a flow rate of 6.8 units per hour. If all other things were equal and the daily rate of 50 units was achieved from a plant operating with two shifts, the flow rate would be half that, or approximately 3.4 units per hour. The calculation would be 50 divided by 7.3 times 2, or 50 divided by 14.6. Flow rates are important in managing the progress throughout the day, particularly in the high-volume manufacturing processes. They are always monitored at the end of a product line. (See Fig. 9.6.3.)

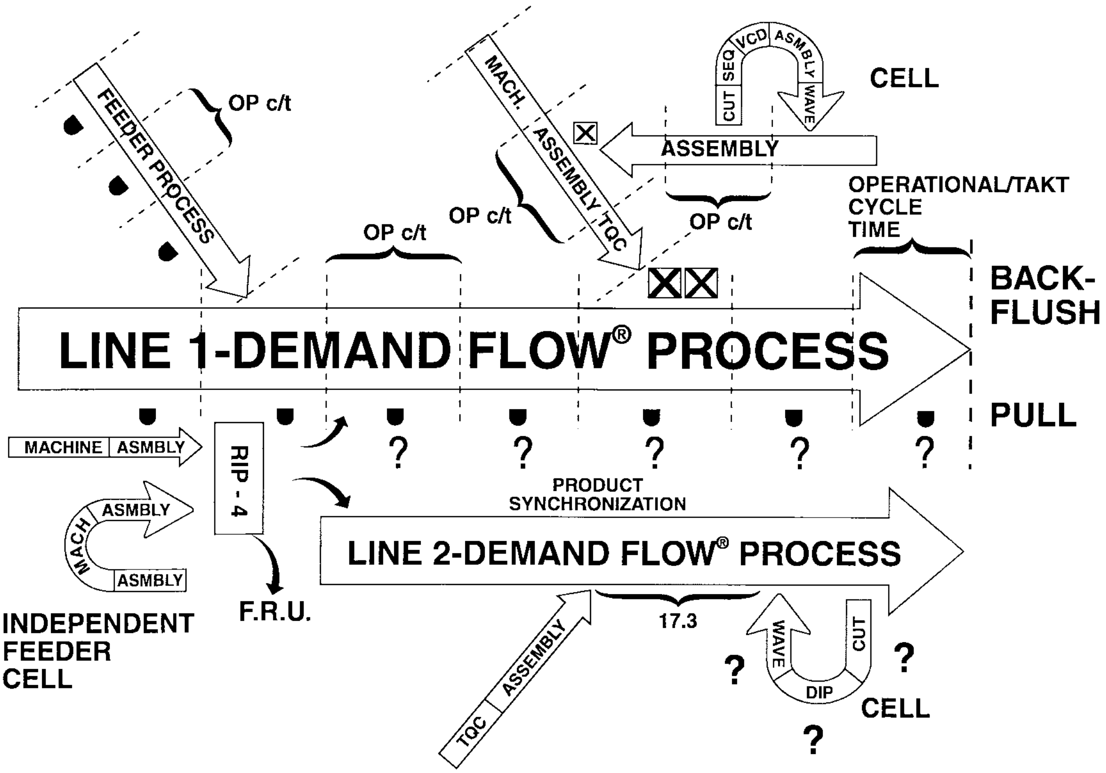
Operational cycle time is based on the designed daily rate or capacity. It is the targeted work-content time required for a single person or machine to produce a single part or product within the flow process. The operational cycle time calculation establishes the takt of the process. It is a calculated, numeric time value based on the *targeted* work content. Operational cycle time is the reciprocal relationship of the flow rate. It is shown as follows:

$$\mathrm{OP\ c/t} = \frac{\mathrm{H(S)}}{\mathrm{Dcp}}$$

where H = effective work hours
S = work shifts per day
Dcp = designed daily rate (capacity)

Thus, simply stated, the operational cycle time equals the effective work hours in a shift multiplied by the number of shifts per day and divided by the designed daily rate capacity. With the daily rate of 5 and 7.3 effective work hours per shift, the one-shift operation would have an operational cycle time, or takt, of 1.46 hours per unit, or (preferably stated) 87.6 minutes per unit.

The operational cycle time formulas or calculations would be used for all flow manufacturing lines, regardless of the product or volume. The targeted work content is identified based on the operational cycle time calculation. The TQC sequence of events is then grouped into pieces of work equal to this targeted work content. These ideally equal, grouped pieces of work are defined as a flow operation.


FEEDER PROCESS
OP c/t
MACH.
ASSEMBLY
TQC
OP c/t
OP c/t
CUT
SEQ
VCD
ASMBLY
WAVE
CELL
ASSEMBLY
OP c/t
OPERATIONAL/TAKT CYCLE TIME
BACK-FLUSH
LINE 1-DEMAND FLOW® PROCESS
PULL
MACHINE
ASMBLY
RIP - 4
?
?
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?
?
ASMBLY
MACH
ASMBLY
PRODUCT SYNCHRONIZATION
LINE 2-DEMAND FLOW® PROCESS
INDEPENDENT FEEDER CELL
F.R.U.
17.3
TQC
ASSEMBLY
WAVE
CUT
DIP
?
?
?
CELL

FIGURE 9.6.3 Designing the flow.

In conclusion, the higher the designed daily rate or the higher the volume required, the shorter the designed operational cycle time and the faster the takt; the lower the designed daily rate or volume required, the longer the designed operational cycle time and the slower the takt. These designed daily rates of products to be produced will determine the corresponding work content required to achieve this targeted rate or volume. Once the targeted work is defined, the TQC sequence of events will be independently grouped into machine and labor operations. Each operation would ideally have actual work content equal to the targeted cycle time of the production line or cell.

Adjusting Volume Output Daily

This designed operational work content and corresponding TQC quality criteria is now defined and basically fixed. To adjust the volume of products required to meet specific rates, either people will be removed from the operations and machines turned off or fewer hours will be worked per day—but the operational work content and corresponding quality criteria is not changed. As an example, the actual volume of products produced may simply be reduced by 50 percent from the designed daily rate (capacity) by removing every other person and turning off the appropriate machines. The flexible production employees simply move from operation to operation, but the work content and the quality criteria at each operation is not changed. The flexible production employees are invaluable elements in the flow manufacturing processes, and their certification, reward, and compensation should reflect their new responsibilities and contributions.

In flow manufacturing, production lines or cells are always designed at the highest required rate and the corresponding shortest required cycle time. When designing a flow line or cell, the manufacturer should seek the anticipated capacity volumes for each particular product from top management and marketing. This required volume must look forward at least a year into the foreseeable future. The flow manufacturer will then calculate the targeted operational cycle time based on this anticipated highest rate to establish the takt of the line. The manufacturer will then design a line with operational work and quality criteria equal to the corresponding takt time.

As discussed earlier, it is not necessary to change a line layout every time a required rate is changed. The flexible employee in the flow process will enable lines to run at lower rates by removing employees from required operations. A line or cell with fewer production employees than the total number of operations is known as a "line with a hole in it." Production employees will move from operation to operation to maintain the pull process. Employees removed from the line will work on employee-involvement tasks, cross-training, and quality improvement programs until the higher volume of products is again required. The "holes" in the flow line will move up and down the line as production employees move to pull work to each operation.

Once the targeted rates and corresponding takt times have been defined and the actual operational work content established, there may be an imbalance between the target operational cycle time and the actual observed operational cycle time. Labor-intensive operations can be adjusted by relocating material or work content between operations to give people more or less work. However, operations involving machines that effectively run at one speed require different techniques to adjust for the imbalance.

The objective is to have the actual work content equal to the targeted operational cycle time. Refer to Fig. 9.6.4 and consider a flow line where five successive operations have an actual work content as follows:

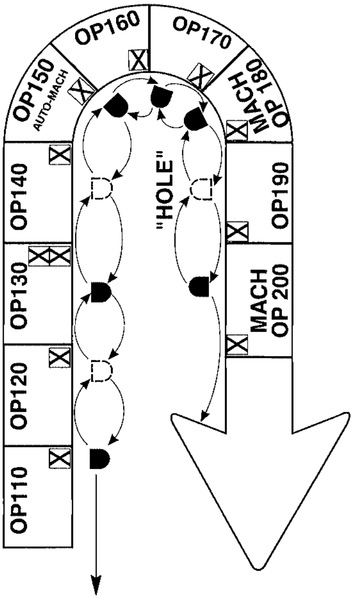

FIGURE 9.6.4 Flow line with hole.

Operation 30, 21.5 minutes
Operation 40, 20.0 minutes
Operation 50, 20.0 minutes
Operation 60, 25.0 minutes
Operation 70, 20.0 minutes

These operations are part of a flow line that is designed to produce 22 units per day. However, operation 60 is a machine operation that produces a unit every 25 minutes—no more, no less. The calculation of targeted operational cycle time is as follows:

$$\text{OP c/t} = \frac{H(S)}{Dcp} \; \frac{7.3(1)}{22} = 0.33 \text{ hour} = 20 \text{ minutes}$$

where OP c/t = targeted operational cycle time
H = effective work hours
S = shifts per day
Dcp = designed daily rate (capacity)

The targeted cycle time of this line is 20 minutes, but the actual time to produce a part at operation 60 is 25 minutes. During the 7.3-hour day, the 20-minute operations would produce 22 parts, whereas the 25-minute operations would produce only about 17 units. Since the line is targeting a rate of 22 units per day and the machine at operation 60 is capable of producing only 17 units per shift, the manufacturer would basically have three alternatives to solve this imbalance problem:

1. Reduce the cycle time of the machine at operation 60 to 20 minutes by eliminating any non-value-added time, such as setup or move time
2. Obtain an additional machine capable of producing at least five units per shift.
3. Create an inventory of units around the machine that would allow the machine to run longer hours than the remainder of the line.

Although the first alternative is always preferred and the second alternative is usually the most expensive, the third alternative becomes the most common choice. The number of units (inventory) required to allow the machine to work additional hours is computed based on the imbalance between the actual time to produce a part and the targeted cycle time of the process:

In-process~kanban above (inventory) = imbalance × cycles of imbalance over operational cycle time

During the 7.3-hour shift, there would be a buildup of five units between operation 50 and operation 60. The machine could work additional time on a second shift processing the buildup of five parts to operation 70 for the start of the next day. At the start of the next day, the inventory in the front of operation 60 would be zero and in front of operation 70 would be five units. This inventory, required to support the imbalance, is referred to as an in-process kanban (see Fig. 9.6.4). Cost of another machine notwithstanding, the imbalance does not appear sufficient to warrant one.

Staffing Changes Flow Rate

Based on the imbalance of units, additional hours of production are needed. They could be provided through a second shift or by alternating operators and keeping the machine running through lunchtime breaks. An in-process kanban containing several units would exist before the machine and before operation 70. This in-process kanban would contain the units produced in overtime or on the second shift, and it would keep the line flowing and achieve the targeted daily rate. If the imbalance was caused by a setup or non-value-added work, that problem could be attacked vigorously. If the work content cannot be balanced, then this imbalance between two operations is handled with an in-process kanban, a point of supply between the two, sized to equalize the imbalance.

The objective in flow line design is for work content to be equal to the targeted operational cycle time. Once this is understood, it is quite possible, for example, for an automobile manufacturer and an ordinary pencil manufacturer to have the same targeted operational cycle time. If eight automobiles were to be produced in an eight-hour day and eight pencils were to be produced in an eight-hour day, both would have the same operational cycle time—one hour. However, there would probably be many more people working on the automobiles than on the pencils. The targeted operational cycle time would be the same, but the number of people and machines would differ.

The operational cycle time defines the targeted work content for each operation. This calculation establishes the takt for each process. Barring a change or improvement to the process and after the line is designed, the operational work content is fixed and no longer rate-sensitive. The number of people required to support a process is based on the labor time per unit—it is very rate-sensitive. Consider a process that has a daily rate of 25 units per shift, total labor hours from the TQC sequence of events of 36.0 hours per unit, and effective work hours in a shift of 7.3. The number of people needed to support the process is derived by multiplying the specific product daily rate by its total labor-hours per unit and then dividing by the effective work hours in a shift multiplied by the number of shifts:

$$\text{People in-process} = \frac{D \times L}{H(S)} = \frac{25 \times 36.0}{7.3(1)} = 124 \text{ people}$$

where D = specific daily rate quantity
L = labor time from the TQC sequence of events
H = effective work hours
S = number of shifts per day

The process requires 124 people. If the line is not running at its designed capacity, there will be holes in the line. The people simply move from operation to operation upon completion of the work content at their primary operation.

These are techniques that would be used to design and balance a flow line. And, once the rate and cycle time techniques have been mastered along with an understanding of the pull techniques, the particular product or related technology used to produce it are irrelevant.

Total product cycle time (TP c/t) is the next key element of the production flow process that will be calculated. TP c/t is the longest path of a flow process as measured from the completion of the product. This is a key value that will be the basis for the inventory investment dictated by the process. It will also be the basis for absorption of overhead in the flow manufacturing financial system. Improvements in the process will be listed in priority along this path with the intent of eliminating non-value-added steps. Total product cycle time is basically a fixed number that is not rate-sensitive and will not change as long as the process is stable. Elimination of non-value-added steps along the TP c/t path will cause the path to move around and change the focus for process-improvement activities. Total product cycle time is calculated as the work content through the longest path of the process to build the product.

In the flow manufacturing pull process, the daily rate is achieved at the completion, or end, of the flow process. The last operation pulls from the previous operation and all the way through to the calculated origin of the product. In the calculation of TP c/t, the end of the line is always the starting point of the measurement (see Fig. 9.6.5). Starting from the end and working up the flow line design to the calculated beginning, the TP c/t path can be determined by taking the longest step at each of the many decision points in the process. Each of those

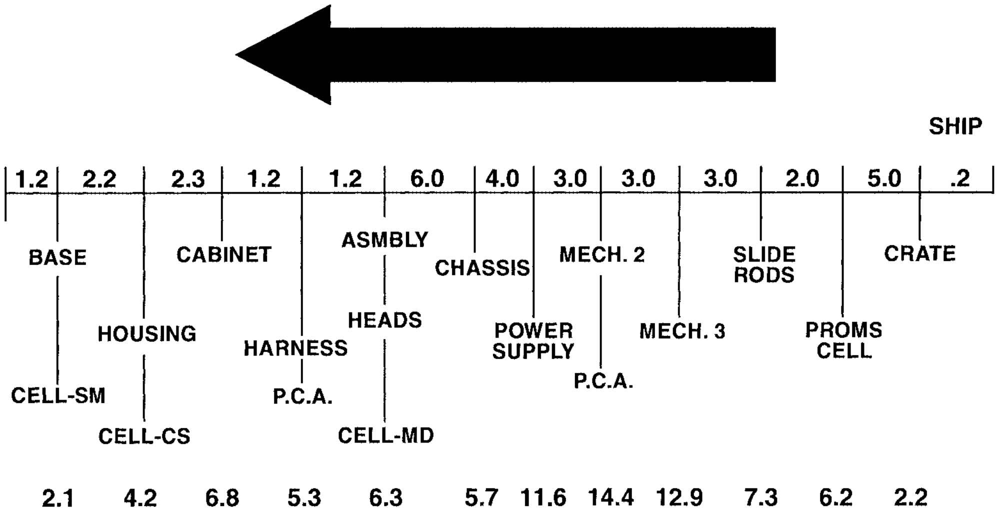

FIGURE 9.6.5 Longest path of flow.

steps represents a discussion or analysis of which path with respective offshoots is the longest. By beginning at shipping, going back through the production process, and moving off to feeder and other side or main processes, the longest path can be determined. This is the longest, cumulative, single path back through the process, regardless of whether it follows the main line or trails off to a feeder process.

Once the total product cycle time has been determined, steps can be taken to shorten it. Based on an improvement to the steps in the process, this path can and will move. Focus must be maintained on total product cycle time. And non-value-added steps (e.g., setups and move time) can be analyzed for reduction. Total product cycle time is not rate-sensitive, and it does not change unless improvements to the production flow process occur.

Analysis of the flow path (total product cycle time) always begins at the completion, or end, of the process. The analysis involves taking the work content, adding back to front at the point in the process where the first feeder is consumed or required for final assembly. Adding the work content time from the back of the process to the point where the feeder is consumed plus the work content time of the feeder process will yield the time through the first feeder. The analysis continues from the back to the next point at which a second feeder process is consumed. Work content time from the back of the process to the point where this feeder is consumed is added to the work content time of this feeder process and compared to the work content time calculated for the previous feeder. The feeder process associated with the lowest number is eliminated as the analysis continues to each point where a feeder process is consumed. The search is for the longest path as measured in time. This will be the total product cycle time required by the flow of the process.

As an example, consider a process that has three feeders, with total time of each feeder as follows: 12 minutes, 20 minutes, and 32 minutes. (Refer to Fig. 9.6.6.)

Feeder process 3 is consumed last in the sequence of events, and after that, 12 minutes of additional work content is done up to the point of shipping. Therefore, the path through this feeder is 32 minutes plus 12 minutes, or 44 minutes. Feeder 2 is needed next, and 30 minutes of work is done after it is consumed. Therefore, the path through feeder process 2 is 30 minutes plus 20 minutes, or 50 minutes. Since this value is greater than the 44 minutes calculated for feeder process 3, feeder process 3 is eliminated from further consideration. Feeder process is consumed first, with 35 minutes of work being done after it is consumed. Therefore, the path through feeder 1 is 35 minutes plus 12, or 47 minutes. This also is shorter than the 50 minutes for feeder process 2, so it, too, is eliminated. Thus, for this process, the total product cycle time through the longest path is 50 minutes, and it would be through feeder process 2.

Total product cycle time is of crucial importance in the Demand Flow process for three primary reasons. First, it dictates the minimal inventory investment required to support the

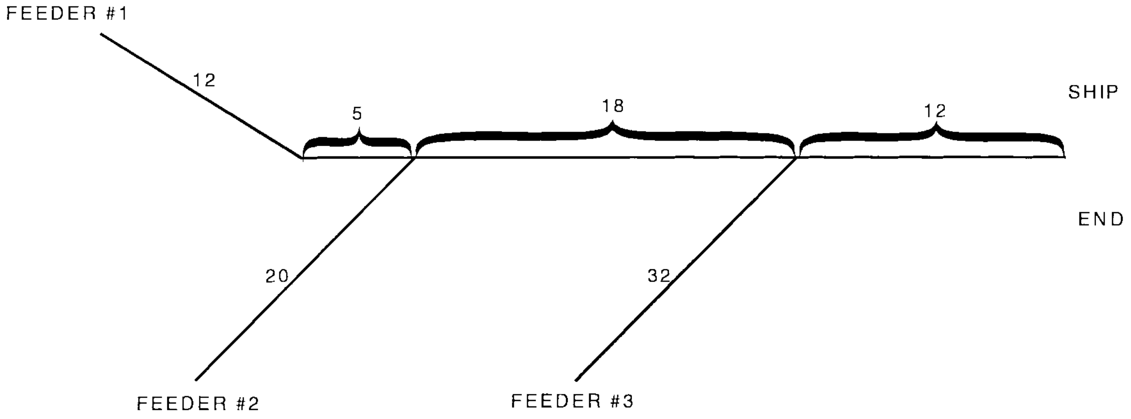

FIGURE 9.6.6 Total product cycle time.

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process. The shorter the total product cycle time, the shorter the amount of time that inventory must be on hand in the production process. In traditional subassembly manufacturing (MRP II), in-process inventory is maintained for the lead-time days, weeks, or months that it takes to schedule, queue, kit and build each level of the multilevel product. In Demand Flow manufacturing, the product can progress through the flow process in less than the total work content hours to build the product. Also, as the total product cycle time is reduced, so, too, is the corresponding in-process inventory investment.

Secondly, total product cycle time is crucial because it is the basis for the application of overhead. The efficient Demand Flow manufacturer will not apply overhead based on labor, since labor is not a primary focus and is the smallest (and shrinking) portion of product cost. Total product cycle time is a consistent and fixed basis for the application of overhead. As total product cycle time is reduced, overhead is not fully absorbed. Pressure is applied to management and marketing to focus on additional products or to enable additional volume to be supported in the process with the same overhead. Traditionally, underabsorption of overhead is a negative feature. It can mean that an insufficient number of labor-hours (inventory) has been produced to meet the budget. This can cause the inventory to be built up to absorb the overhead. In Demand Flow manufacturing, the underabsorption of overhead, because of the reduction of the total product cycle time, can be a powerful management tool to force process improvements.

The third primary purpose of total product cycle time is that it serves as a guide for the process-improvement program. The priority of the process-improvement/employee-involvement program should be emphasized along the TP c/t path of the process. The dominant global Demand Flow manufacturer must strive to reduce non-value-added steps in order to reduce the inventory investment time and reduce total product cycle time along with the corresponding absorption of overhead.

Inventory Investment and Total Product Cycle Time

The in-process inventory investment in Demand Flow manufacturing is dictated by the total product cycle time. Reducing total product cycle time is a primary objective. Total product cycle time is determined by the work content along the longest path of the process, which is usually a shorter period of time than the total work content, or the total amount of time it takes to build a product. As an example and using an oversimplified line layout, the total time it takes to build a product may be 20 hours. That may include an 8-hour feeder process that is consumed toward the end of the line. If the consuming line is a totally sequential process of one step after another for 12 hours, the longest path could be 12 hours if the 8-hour feeder process occurred simultaneously. Even though it takes 20 total hours to build the product, parts and raw materials (all inventory) need only be in the process for 12 work hours. Shortening the total product cycle time to reduce the time inventory must be present, and increasing the material turnover is a primary objective from a financial standpoint.

Single-digit inventory turns are no longer acceptable, and they can cripple a corporation's competitive power. Traditional techniques, methods utilizing the schedule-based formal systems (MRP II), will produce traditional results. Achieving competitive goals of 24 to 26 inventory turns annually as a minimum will require nontraditional techniques and systems.

Demand Flow Is a Companywide Strategy

The adoption of Demand Flow manufacturing technology should not be an optional choice for the various organizations or individuals in a company committed to becoming a globally dominant manufacturer. It is a technology that, once adopted, must be fully supported by top management and driven across all organizational boundaries. It is a companywide program in which management must be committed to change. The Demand Flow manufacturing methodology is focused on the two major elements of product costs: material and overhead. Demand

Flow manufacturing techniques are used to develop a powerful production process that utilizes pull systems with in-process quality as the number one objective. Achieving the elite goal of a globally dominant manufacturing company requires the establishment of nontraditional goals and the implementation of nontraditional methods of managing the process.

Company reasons for implementing Demand Flow manufacturing are simple:

- Customer responsiveness
- Quality improvement
- Overall cost reduction
- Survival

American companies are becoming more proficient at reducing costs. However, many of those cost reductions are obtained by cutting an arbitrary percentage of employees to maintain profitability rather than through productivity, quality, or process improvements.

Demand Flow manufacturing should never be perceived as a workforce reduction program. While it is true that the Demand Flow manufacturer will require a significantly smaller number of resources in some areas, other areas will require more resources. Demand Flow manufacturing improvements allow the same workforce to produce higher-quality and lower-cost products, thus inducing marketing to sell more goods with no (or only marginally) increased costs. Retirement and attrition will take care of any workforce adjustments. Support of the DFT implementation program from all levels is mandatory for the implementation to be successful. Ways of utilizing the workforce, freed from traditional functions, must be examined as part of the implementation process.

As manufacturing technology evolves from the traditional, labor-tracking, scheduling, batch mentality to the Demand Flow technology, the way in which people are involved in the technology changes as well. People are the most important asset of any company. In a Demand Flow manufacturing environment, the responsibilities and work content of many employees change. As the roles change, the organizations that support the people tend to change. In traditional manufacturing, people are told what to do and how to do it.

The traditional manufacturing company consists of many layers or levels of management. Information, goals, expectations, and philosophies tend to become transformed as information is passed down through the various levels. The phenomenon is rarely intentional, but each level brings a unique perspective to events and a unique interpretation of information. By the time the information reaches the people or the level for which it was originally intended, it might bear little resemblance to the initial message. Direct exposure of the lower tiers of the organization to the upper echelon of the company is infrequent and formal in nature.

Furthermore, information passed from the bottom up through the levels of the organization suffers the same fate. Middle-level managers typically do not want to bother higher levels with details and information from the ranks. The information becomes more heavily summarized each time it gets passed to a higher level. The information also suffers from a phenomenon known as *filtering,* in which information detrimental to the middle levels is hidden or buried in statistical gobbledygook. This is human nature. but it makes it very difficult to get the proper information to the proper decision maker in a timely fashion.

The future success of U.S. manufacturing lies within the global marketplace. An examination of the underlying root causes of inefficiencies within U.S. manufacturing reveals that problems reside in management practices, organizations, and compensation strategies. As U.S. companies attempt to compete and to survive in the global market, the following things become clear.

Flexibility, Participation Come of Age

- Flexibility is a valued skill in a company. The age of specialization is over. No longer can the workforce focus on a narrow range of skills. The markets and companies are changing too quickly.

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- Participative management is a concept whose time has come. As organizations become leaner in an effort to remain competitive, they must utilize the resources that are available. They need to harness the creative problem-solving abilities of the workforce as well as to utilize technical and administrative skills. Participative management means that, in advance of implementation, those people whose responsibilities will be affected get to participate in making the decisions.

Involvement, Compensation Change

- Employee involvement must become an ingrained part of the manufacturing culture, an integral part of a company's way of doing business. A giant leap of faith must be taken by assuming that the person who is actually performing a job knows best how to do it and how to improve it. It is essential not only to get input from the operator but to act on that input as well. A flood of employee recommendations often follows the launching of an employee-involvement program. Many of the improvement suggestions are not even investigated. Employees become disillusioned and stop participating. In most cases, a nonexistent employee-involvement program is better than a nonsupported employee-involvement program.

FLEXIBLE EMPLOYEES

Globally dominant manufacturing is accomplished through people—people play a more dramatic, extensive, and critical role than in traditional manufacturing methods. Employees get more training and do a greater variety of operations. They have more and different responsibilities. That is why they are called *flexible employees.* They are paid for their flexibility rather than their seniority. Production employees are responsible for quality, and, unlike in traditional manufacturing, the production employees can stop the line. Production employees can be trainees and trainers. They can move to leadership positions or to replenishing the kanbans if a material handler does not come around.

Production employees in Demand Flow manufacturing must be able to work "one up" and "one down" at a minimum. They must be able to do the operation on either side of them; they must be able to do at least three different operations: their own, the one immediately before it in the process, and the one immediately after it in the process or cell. An employee at the beginning of a process must learn one position up and the operation of the immediately preceding process; an employee at the end of the process, in addition to learning one position down, must learn the next operation in the next process or that of material handling.

If a production employee reaches for a unit to work on and there is no unit there, that employee moves in the direction of the pull and works on a unit to supply the empty station. The employees are not told to do this—it is an automatic response to the absence of units flowing to their station. Employees can help complete the units flowing to their station and then return to their station, or the next operator down the line can move down and take the position in the then-vacant station. The process and movement of employees is that simple: an employee goes to pull a unit, there's nothing there, the employee moves in the direction of pull.

That is in marked contrast to traditional manufacturing in which, if no product were there, the employees would remain at their idled positions and perhaps make a report of the situation. If fewer people are in the process, although the work content has not changed, the observed operational cycle time increases. Due to employee flexibility in the Demand Flow manufacturing system, this is a process that can run with 50 percent of the employees absent. Although the observed cycle time will increase and the volume of products will decrease proportionally, the Demand Flow manufacturing process can run smoothly if every other employee is absent. Conversely, if there is a need to produce fewer products, employees can be pulled, and the process will balance itself. In high-turnover situations, one up, one down is even more beneficial. No matter how many holes in the process must be plugged by the flexible employees, verification and total quality control are still performed, and work content does not change. One up, one down is the minimum requirement to work in a Demand Flow manufacturing process. Once this is attained, the employee may decide to reach further flexibility standards, such as two up, two down, three up, three down, and so forth. Eventually, certification in all process operations may be reached by a few employees while others choose to stay at the minimum level of one up, one down. Employees usually pursue flexibility horizontally and vertically (e.g., doing several different assembly operations and doing assembly, testing, and machine troubleshooting).

After an initial training period, all employees in a DFT environment will be certified in a minimum of three positions. Employees must know their primary positions plus one position up and one position down from the primary. This is required for several reasons. Since employees must verify the previous work content sent to them, they must be familiar with the work content of those positions. They must also be aware of the following position's work content, whose operator will verify their work. Also, management will run various flow lines at different rates. Employees will be inserted or pulled out of a line based on the current rate of the lines. Each employee does the work and quality defined by the DFT method sheets in that operation. As rates decrease, people may be removed and machines turned off, but the designed work content and quality criteria at each operation do not change.

Flexible employees allow management to adjust the volume of products being produced without changing the operational work or quality criteria of an operation. These employees can move to alternate operations without mass retraining efforts. The pull process requires flexible employees. Flexible employees are allowed to fill their in-process kanban and complete the unit at their station or machine. At this point, their demand is satisfied and they must move downstream. They will then assist at that position until a unit is completed at the downstream operation. The flow line naturally rebalances with flexible employees. Employees must be able to perform upstream and downstream operations in order to make the pull process effective. After the basic requirement of one up, one down is met, additional flexibility of the employee should be encouraged and incentives provided. Since flexible employees are required to rotate frequently through certified operations, a cap would be dictated by the number of operations an employee could reasonably be expected to perform over a given period of time.

An element of an employee's flexibility is tied to participation in the employee-involvement program. This will differ from the traditional suggestion program in several respects. First, there will be a formal response process embedded into the program. A nonexistent employee-involvement program is better than a nonresponsive one. Employees will be encouraged to suggest process improvements. These improvement ideas can include elimination or reduction of non-value-adding setups and moves as recorded on the DFT sequence of events, elimination of non-value-adding TQC criteria, improvements to the DFT operational method sheets, improvements in workstation layout, and input into new product development for the elimination of variables. Often, suggestion programs flounder because resources are not available to respond to suggestions. The biggest impact is typically on design, manufacturing, and industrial engineering. Suggestions should go beyond the typical solution steps of identifying the problem, gathering data, isolating root causes, and monitoring. The suggestions should be made in a team mode rather than an individual mode. Teams should have incentives to make suggestions, not necessarily to find solutions. The more support functions embedded in the team, the greater the success.

An active training program is essential to enable employees to attain and maintain flexibility. The first phase consists of the nontechnical training required for working in the process. The quality department will provide Pareto and process control training. Human resources will provide team, employee-involvement, effective meeting, and interpersonal skill training. Employees will be provided information on the company, its products, customers, values, and missions. This phase is a continuous one provided to all employees. It seeks to eliminate one of the shortcomings of traditional manufacturing where employees who help assemble a product may have no idea what the finished product looks like and are unfamiliar with the company's goals. This effort is a part of the team-building process and as such is quite important. State-of-the-company presentations should also be given quarterly by upper management to all employees in an open and frank manner with adequate time for questions and feedback.

The second phase of training is off the line, where employees are taught basic production skills in an off-line but simulated production environment. Verification and TQC recognition from method sheets are also taught. Usually three days to two weeks of off-line training are provided.

The third phase of training is on the production line. A trainee will work in the process with an experienced employee who has obtained a mastery level. The trainee may actually perform the work under the guidance and scrutiny of the skilled employee. The employee at the mastery level is responsible for the quality of the work being performed. During this phase, the trainee will become familiar with the certification criteria for the operation. These certification criteria will include technical aspects of the operation, quality criteria, and how often an employee must perform the function in order to achieve and maintain certification levels.

Certification criteria for a position must be clearly defined. These criteria must include technical work content, educational requirements, quality expectations, and the maximum amount of time that can pass between assignments at that position. A *position* is a combination of events that have been grouped together based on the targeted cycle time of the flow process. A position is not each and every sequence of events in a process, but a grouping of the sequences. One-up, one-down positions may be within what is defined as a *job* for job banding. A team of production, quality, engineering, and human resource people will perform the job-banding function and create the certification criteria one time. Some jobs or positional criteria may change over time, and a system needs to be put in place to modify the bands or criteria.

Mastery criteria are based on two differentials from certification criteria: (1) the production of high-quality parts for a proven period of time and (2) the ability to train and certify others. Some employees may be fine at a particular craft but couldn't train fish to swim. They will stay at the certification level. For those who wish to attain mastery level at an operation, the company must provide an adequate training program to train the trainers.

Once certification criteria are clearly defined, the possibility of meeting these criteria should be made available to all employees in that process. Training programs should be developed to enable employees to reach higher levels of flexibility. After-hours classes can be offered to the employees to further increase their flexibility, particularly of the vertical variety. This may enable today's production employees to learn, through their own initiative, preventative maintenance or test-tech skills that can someday increase their value to the process and increase their pay as well.

Employees may become decertified in a process due to failure to meet designated criteria, most likely not working in a position often enough to maintain certification. This decertification process is palatable to the employees if they feel they have control over where they work. If opportunities are not given to exercise flexibility, and decertification occurs, the employee will feel that it is an unfair action. The determination of who works where and when is a duty of the team leader, who needs to be aware of minimum certification requirements and rotation intervals.

Team Management System

Different teams cover particular areas of the process. They revolve around two central teams: (1) the team management system (TMS) team, which consists of all team leaders, and (2) the global support team, which includes those outside the process, such as suppliers and marketing. TMS and global support are tied together under the plant manager. Support members are part of a production-oriented team. Improvement of quality is the immediate objective; improvement of the bottom line is anticipated within two or three years.

Team leadership is a commitment to training, better work coverage, decreased communications breakdown, higher employee morale, shared risk, and giving individuals more of a direct impact on their income. The professional status of some is lessened, as, for example, a senior staff engineer becomes a part of a team. There are no functional boundaries to serve as obstacles. Career paths and roles may change. A person without a degree may wind up supervising someone with a master's degree. The new mix and increased flexibility means that others can enjoy increased pay and stature that is directly related to their own efforts.

The Demand Flow companies have demonstrated an uncanny ability to focus on material cost—a far greater ability than that of most schedulized companies. Emphasis in the United States for many years has been on labor costs, even though labor on most efficient processes has dropped to between 5 and 15 percent of product cost. Meanwhile, the material and overhead portion of total product cost has soared to 85 to 95 percent.

Demand Flow manufacturing applies homogeneous overhead to a basis of total product cycle time. Applying homogeneous overhead to total product cycle time does not penalize production for becoming more efficient. Total product cycle time has a direct relationship to the amount of homogeneous overhead consumed and the rate at which inventory turns over. Traditionally, applying overhead to direct labor increases the amount of overhead per production head count if production becomes more efficient and labor work at an operation is eliminated. Applying overhead to material will dangerously increase the amount of overhead applied if an assembly or fabricated part is subcontracted out and the standard material cost is increased or if two products with similar work content are made from materials of vastly different value. Applying overhead to material will create a focus on reducing material costs and turn into a supplier cost-reduction program. This also removes the focus from the production process, which in turn sacrifices the benefits achieved through the continuous improvement of the TQC flow process.

FLOW-BASED COSTING OF PRODUCTS

Establishing the Standard Product Cost

The standard product cost will still contain the basic elements associated with the following:

- Material
- Labor
- Overhead

Labor (direct and indirect) will *not* be tracked against an operational efficiency standard. Since production employees are now required to fill holes created in processes that are producing at less than capacity, exactly which person produced what quantity is considered to be inaccurate and meaningless information. Labor costs will become an element of overhead costs.

Overhead costs will now contain all factory costs associated with the conversion of purchased material plus "touch" labor costs. This homogeneous overhead cost will be applied to the total product cycle time for each product. Also, a variable overhead cost may be created to account for extraordinary conversion costs driven by the use of special machines or resources. Only the products that require the use of these expensive resources would absorb these extraordinary overhead costs. This extraordinary overhead cost could also be allocated based on the square footage that the manufacturing process occupies. Other variable overhead costs can also be charged per square foot of manufacturing space occupied, per hour of planned usage, and for product-specific resource requirements. (*Caution:* There is a tendency to overmanage extraordinary overhead costs. Do not microscopically explore your facility for these costs. They should be obvious and readily apparent.)

To establish the total product cost, the purchased material content of a product must also be identified. The bill of material in Demand Flow technology must be 100 percent accurate in order to back-flush inventory. Each product's bill of material will be costed out at a total raw material standard cost. Purchase price variance will be measured by comparing the actual purchase price versus the raw material standard cost. The cost of carrying inventory should also be added to the total cost of the raw material, not to the standard raw material cost. In the analysis of actual costs versus planned standard costs, the actual overhead and actual TP c/t would be used in physical audits of TP c/t to monitor progress.

Industrial engineering should be the leader in the reduction of total product cycle time. In changing from departmental and schedulized manufacturing with labor-based cost accounting to flow-based techniques, the production process must be changed first. The new role of industrial engineering is to change from a labor-efficiency focus to the improvement of manufacturing response time to the customer. The focal point should be on the process and process improvement, including manufacturing, procurement, costing, and planning.

Once a company has adopted the Demand Flow business strategy, the emphasis will focus on customer response (no late shipments), zero working capital, inventory turns, elimination of unnecessary, non-value-adding steps, and the reduction of overhead costs. The use of automation is to be questioned when it cannot support daily mix and volume changes. Industrial engineers must understand Demand Flow business strategy, as they will be expected to help lead the pursuit of the elite zero-working-capital company.

PERFORMANCE MEASUREMENTS AND REPORTING IN DFT

Several different tools can be utilized to manage the Demand Flow process, including TP c/t, flow rate, linearity index measurement, team passes for nonquality items, the number of line stops or time per problem, in-process kanbans, inventory turns, and employee involvement. The most important goal of the DFT production process is to produce a total quality product. Quality is never compromised for any reason. Once the quality of a product is ensured, the next goal is to make quality products equal to the daily rate. If the daily rate is 100 units for the day, the goal will be to make 100 units—not 95, not 105, but the 100-unit daily rate. The method of measuring and auditing a Demand Flow process is significantly different from that of traditional manufacturing. With the flexible employee, individual performance measurement is neither practical nor warranted. All measures will be team measures.

The Demand Flow manufacturer should monitor the total product cycle time of the flow process. If the calculated total product cycle time is one hour, the manufacturer should physically go to the production process and audit this time. Unfortunately, it is not possible to audit actual total product cycle time by remote control—it must be physical. If process improvements have been made since the last audit, it may be reasonable to expect the total product cycle time to be reduced. Overhead would then be underabsorbed for that process.

Also closely monitored will be the linearity index. Once a 96 to 98 percent linearity index against the daily rate is achieved, the Demand Flow manufacturer may start to measure actual production flow rates at the back of the process. An 80 to 85 percent linearity index against flow rates is an excellent flow line. Support team resources should be close to the process they support. It is the responsibility of the team leader to get these resources when process problems occur. Support team resources cannot be enlisted by remote control, either—they must be in a position to respond quickly to process problems.

A team pass is another measurement of a total quality flow line performance. This occurs if the unit was produced incorrectly and not correctly validated at the following TQC operation. The unit will be returned for rework. Although the reworked unit is now perfectly acceptable from a customer, marketing, and financial perspective, it will not be counted toward the daily production linearity goal. The use of a team pass can invoke powerful peer pressure in the process. If a unit requires rework, it is tagged with the pass of the team responsible for the rework. The unit goes through the entire remainder of the process with the team pass. The product is not credited to the team goal. There is no way to make up for the team pass, and there is no way to regain credit for the reworked unit. Just like defective work in a customer's hands, non-TQC work in the plant represents a nonrecoverable situation. The percent of team passes and the deviations against the daily rate are tracked each day.

Individual employee tracking and reporting in a Demand Flow process is neither feasible nor desirable with the flexible employee. The reporting in a Demand Flow process will be simple, direct, and meaningful. Labor and machine content per product/process in total hours per unit will be known and reported. This will be the basis for how many people will be needed in the process at a given rate. Cycle time, both total product and operational, will be monitored. Two operational or team passes will be monitored and reported. The number and duration of line stops will be tracked. Inventory levels of purchased material and in-process kanbans will be monitored and reported. Continual improvement in these measures will be expected through the employee-involvement program. Pareto charts, control charts, and fish-bones will be utilized extensively. Reporting will be very visible and on a team basis. Managing a production process also involves maintaining employee certification charts and criteria and determining where each employee's primary position will be on a daily basis.

Computers and Demand Flow Technology

The technology and methodology of Demand Flow manufacturing drastically change the role of the formal computer system. Many of the execution techniques of Demand Flow manufacturing can be done without a computer. The computer must become a tool to support Demand Flow technology manufacturing. In Demand Flow manufacturing, the computer becomes a valuable tool in relation to the following tasks:

- Back-flushing transactions to get material out of the process
- Engineering operational evaluations
- Operational line balancing
- Daily process linearity calculations
- Linear rate indexing
- Kanban management
- Kanban pull sequencing
- Kanban sizing
- Calculating operational cycle times
- Calculating total product cycle times
- Financial applications of overhead to TP c/t
- Method sheet design and management
- TQC sequence of events
- Developing demand-based rate planning (rather than scheduling)
- Processing accounting standards from the sequence of events

Demand Flow technology emphasizes management by eyes and management through use of people rather than attempting to manage externally by reports. Demand Flow manufacturing techniques substantially reduce the number of reports, part numbers and eventually suppliers. Blanket purchase contracts are used in Demand Flow manufacturing, and releases are made against these contracts. The computer in Demand Flow manufacturing is also used to track contracts, transportation networks, and packaging considerations from the purchasing standpoint rather than in the traditional use of detailed, scheduled purchase orders. Typically, company computer transactions will be reduced by between 50 and 90 percent in flow manufacturing compared to MRP II. In Demand Flow manufacturing the computer is not used for scheduling, picking kits, routing, or tracking. Immediately, this tends to render the MRP II shop-floor control system useless. The formal Demand Flow manufacturing system becomes a simpler and more concise management tool. The time and complexity of use of computers in manufacturing peaked with MRP II and has decreased with Demand Flow manufacturing.

When converting from MRP II to Demand Flow technology, the type of computer needed may shift from powerful, centralized mainframes to individual workstations of personal computers attached via a local area network (LAN). There are two main reasons. First, the personal computer has become very powerful. Second, there are far fewer transactions in Demand Flow manufacturing. The personal computer in recent years has put the specialized computing power into the hands of the user. Previously, such power was highly centralized, highly bureaucratic, and guarded from a technological standpoint. The Demand Flow manufacturing computer software and system must be as flexible and responsive as the manufacturing technology it serves.

Traditionally, there is a standard routing, and this has *no* relationship to the TQC sequence of events. The traditional MRP II routing system relies on the bill of material to structure independent processes, fabricated parts, and subassemblies. In Demand Flow manufacturing, the bill of material is a "pile of parts," and the process is controlled through the TQC sequence of events. The TQC sequence of events requires support on the computer to identify which events of the sequence of events are value-added and which are non-value-added, which steps are setup and which are move, and most important, to identify the quality criteria for each element of work. Once the information has been entered into the computer, it can help identify the targeted work content and quality criteria for each operation. This is based on the targeted operational cycle time calculation established during line design. This is a very valuable tool during the initial flow line design as well as for the ongoing process improvement design changes. The computer can also assist in the identification of any non-value-added events in the TQC sequence of events. It becomes a valuable management tool in determining what should be attacked for reducing the total product cycle time.

DFT BILLS OF MATERIAL AND ENGINEERING CHANGES

The bill of material is important in traditional manufacturing, but it is doubly critical in Demand Flow manufacturing. It not only controls the parts to buy, it also controls the inventory. The bill of material requirements of a DFT system should have the capability of taking a traditional multilevel bill of material and compressing it into a single-level bill of material. If you are designing a DFT system, you should give the user the capability of determining whether the subassembly part number should be eliminated, should be restructured independently as a field replacement unit (FRU) or should remain as an additional level on the bill of material. Other major changes in the creation of a bill of material's format include the DFT manufacturing "pending engineering change." This allows the material requirements planning algorithm to correctly identify and plan the purchase of parts associated with the engineering change order based on the approval date of the engineering change order, but will not yet modify the bill of material for back-flush or configuration control purposes. The bill-of-material system must also contain back-flush locations and deduct identification information. Although there is only one bill of material, different lines (line IDs) in different plants can have different back-flush locations and deduct identification information. The bill of material "where-used" system must have the capability to identify which method sheet contains a specific part number. If an engineering change affects a specific part number, the design and process engineer needs to know which method sheets are affected when the change is approved.

DFT Management Techniques

The bill of material must also have the capability of identifying the back-flush information required for inventory management and control. Intermediate back-flush capability at a user-defined deduct point should also be provided. The single-level bill of material is key to a lower number of transactions. In traditional manufacturing, material requirements planning individually processes through each level of the bill of material whether or not there are any requirements for each level of the bill of material. Computer processing goes through those levels one by one. This is one reason that material requirements planning runs in large companies may take an entire weekend to complete and process. Because of the DFT manufacturing flat bill of material along with the elimination of the work order system logic, material requirements planning can now run in a fraction of the time.

DFT Method Sheets

Demand Flow technology method sheet information should also be kept on the bill of material, and the method identification number should be tied to a line item on the bill of material. As discussed earlier, when an engineering change is made to the DFT bill of material, the software system can point out the method sheets that are affected and those that may need review and modification. An eventual goal is to link the manufacturing system bill of material with the CAD design systems. With that connection to the design process, CAD information can be used directly by the manufacturing system to aid in method sheet design and bill-of-material creation. Although the bill-of-material information may be managed by separate organizations, there should be only one bill of material. The design or product engineering group, whichever is responsible for the form, fit, and function of the product, will control the pile of parts. The back-flush location and deduct identification information will be controlled by the people in planning or production. The security for the change capability of the bill of material must be segregated accordingly.

The difference is obvious when comparing the processes. The DFT manufacturing pull system uses the following:

- A demand-based system for planning long-range material requirements
- Releases generated against a blanket purchase order for the preferred single supplier
- Material receipts directed to raw-in-process inventory
- Materials relieved by a back-flush transaction

Traditional MRP II uses schedules in a push fashion to control the schedule of purchase orders and work orders. After the order is scheduled, material is issued from a storeroom and the work order is released to production. Purchased parts are received from a particular purchase order line item and transacted into the storeroom until they are required to be issued to a work order.

Computer tools and techniques employed in Demand Flow technology are very graphically oriented. System reporting will use many charts and graphs in reporting data for analysis. Graphic computer techniques are used to create pictorial method sheets, graphics on total quality performance, Pareto charts, process capability analysis, fish-boning, and so forth. From a manufacturing engineering standpoint, advanced graphics techniques are used to create graphic production documentation rather than the traditional text-oriented production documentation.

These graphic production documents or operational method sheets represent an exceptional tool for the quality and performance of work in the process. Verification and total quality control by production employees is now possible. These sheets feature a large, colored illustration that graphically directs the operator to points of work and verification. Red lines or other manual modifications will no longer be tolerated, as they defeat the TQC thrust of the operational method sheets. Personal computers and technical illustration software can be used to create such sheets in minutes.

SUMMARY

The world is changing. Results and techniques that worked in the past will not be good enough in the future. Traditional manufacturers will never evolve into dominant competitors.

Tomorrow's leaders will be visionary corporate leaders who desire results that are a quantum leap beyond those achieved by the techniques, methods, and systems currently in place.

Demand Flow technology becomes the foundation for a globally dominating corporation. Business strategies take advantage of the quality and customer-responsive benefits to dominate markets and industries. TQC sequence of events, total product cycle time, operational cycle time, and method sheets are tools and techniques necessary for developing the basis for a flow production process. The process should begin with identifying the natural product flow, work content, corresponding quality criteria, and non-value-added steps through the sequence of events process. Then the operational cycle time will be calculated based on the highest required rate. DFT method sheets will be created to identify work content and quality criteria graphically at an operation based on the targeted operational cycle time. Total product cycle time will then be calculated as a guide to inventory investment, overhead absorption, and process improvement. By identifying these essential building blocks of the Demand Flow process, the dominant global manufacturer has the framework for a powerful, competitive tool. With additional market pressure from powerful new competitors and the shortened product life cycles, these techniques will become essential to industry leaders of the twenty-first century.

Manufacturing is at a crossroads. In one direction is the continuation of the death spiral toward a service-based economy, with the inevitable decline in the standard of living for future generations. The other direction holds a renewed commitment by individuals and companies to be the best in the world. To be the best is to be leaders in the speed-to-market implementation of technology—to produce the highest-quality products at the lowest possible cost and to use manufacturing as a profit-generating competitive weapon.

BIOGRAPHY

John R. Costanza has been a recognized practitioner, author, and adviser in the manufacturing industry for more than 25 years. Prior to founding the John Costanza Institute of Technology, Inc. (JCIT), Costanza worked in senior management, manufacturing, design engineering, manufacturing engineering, and materials management for such corporations as Hewlett-Packard and Johnson & Johnson. He extensively studied international manufacturing and engineering technologies and had the opportunity to observe the results as they were implemented around the world. Based on his international study and implementation success of a mathematically based flow manufacturing technology, Costanza expanded the technology to include all elements of the corporate business strategy, and he is recognized as the "father of DFT," the person who formalized the Demand Flow® technology and business strategy. He founded the international manufacturing technology centers known as the Worldwide Flow College as part of JCIT. He teaches and implements his Demand Flow technology to enable manufacturing corporations to compete on a global basis.

Costanza is president and chief executive officer of JCIT, which is headquartered in Denver, Colorado, with offices in San Jose, California, and Nice, France. For six straight years, JCIT has received the prestigious number one rating for manufacturing education and implementation, having trained over 55,000 students from 3,700 corporations in 42 different countries. Costanza continues to direct DFT implementations throughout the world, in addition to designing and expanding the Demand Flow technology curriculum for the Worldwide Flow Colleges, lecturing, and implementing the business strategy and Demand Flow technology. He often speaks at top-management conferences and serves as adviser to organizations worldwide.

CHAPTER 9.7

AN INTRODUCTION TO SUPPLY CHAIN MANAGEMENT

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This chapter addresses supply chain management and incorporating the larger supply chain business model into all manufacturing and production processes. Supply chain management is dynamic; new systems such as advanced planning and scheduling (APS) have made inventory management and heightened customer service via accurate order delivery a reality. This chapter will review the evolving role of industrial engineers in supply chain management.

INTRODUCTION AND BACKGROUND

The concepts of supply chains and supply chain management have evolved into one of the most important management concepts of the last decade. The increased focus on the process of getting products to market—and managing this global process effectively—is having an important and positive effect on the economics of manufacturing. The use of supply chain management concepts has also begun to produce large benefits in the competitive environment—faster and more reliable deliveries are becoming the standard. An understanding of the principles and practice of the supply chain has become a requirement for industrial engineers.

The supply chain goes far back in history. Some of the earliest indications are transportation records written on clay tablets documenting grain transactions between "warehouse" and customer. Today's supply chain concepts are rooted in the 1961 publication of *Industrial Dynamics* [1]. This work identifies the complex interactions and behavior of multistep information processes, which were previously thought to be rather benign.

In the broadest sense, supply chain concepts cover everything from raw material arrival through delivery to retail customers. However, this chapter will focus primarily on the manufacturing operations and the suppliers to these manufacturers. The downstream activities of logistics and distribution are covered in a separate chapter of this handbook. When we use the term *supply chain* in this chapter, we will use it to mean the process from component supplier to intermediate processors and on through the manufacturing facility of the end item. In the recent evolution of supply chain ideas, Forrester's concepts have been extended by the introduction of integrated, multicompany information structures driven by modern computing and network communication technology. This discussion will be limited to these technology-based strategies.

The image of the supply chain flow as a chain of activities is useful to depict the interrelationship of the participants. But in reality it is much more complex. At each stage in the process there are make/buy choices. And at each of these decision points there may also be multiple suppliers, each of which may have additional make/buy options. In its dynamic reality, the supply chain is the most complex and challenging element of the process of delivering end products to customers.

The first step in the design of a supply chain strategy is the management of the manufacturing operation. The complex nature of the flows through the manufacturing conversion process has always presented a challenge to engineers and managers. MRP systems in the 1970s treated the factory as a black box with a predictable lead time, leaving the details of the internals of the factory largely unchanged. More recently, there has been a new interest in the subject of internal factory flows. This interest has been sparked by the recognition of the crucial role that the factory planning and scheduling process plays in the internal and external stability of the entire supply chain and in the logistics and distribution system. The recent introduction of a new technology called advanced planning and scheduling (APS) is designed to meet the needs of these manufacturing operations. This technology is the single most important development in the history of supply chain management because of its effect on the predictability of deliveries. Because of its dramatic supply chain impact, we will cover APS extensively in this chapter.

The second step in creating a supply chain process is selecting a form of inventory management. This selection may prove to be the most difficult of decisions because there is no fixed, or right, answer. The combination of business objectives, manufacturing processes, and corporate boundaries requires unique inventory management solutions for every enterprise. Rather than attempt to enumerate all the possible options, this chapter will review core principles of inventory management. As a summary of standard inventory management methods, *Factory Physics* [2] offers a detailed compilation.

A third step, regarding the increase in dynamic and real-time operation necessitated by increasing customer demands, will also be addressed. According to a report titled *Customer Trade* [3], manufacturers must modify their business processes to meet customer-driven requirements, whereas previously the manufacturers set trade rules. Customer trade is the first fundamental change in trade practices in several hundred years—the latest industrial revolution. The business systems designed to support the needs of the 1980s are largely obsolete in the 1990s and early 2000s.

To date, no clear consensus exists on how systems must address today's new challenges, but it is clear that the skills of industrial engineers (IEs) will play an increasingly important role in the application of technology. The analysis and design of complex systems has historically been the primary role of industrial engineers. The work of Alan Pritsker [4] has been the foundation for most of the progress in the field of large-scale systems. One of the developments to come from the Pritsker work is the rise of discrete event simulation technology as one of the most important tools of the industrial engineer. Because of the ability to apply this key technology in a new problem set, industrial engineers will need to extend the use of the technology to the supply chain.

As these new concepts of operation have evolved, several core principles of our operating assumptions will be left behind. These concepts will be identified when possible, and the limits of applicability will be defined. Unfortunately, IEs will be left largely to their own devices in some of these areas, since a true understanding of which technologies will survive is never clear until long after the fact.

SUPPLY CHAIN CONCEPTS

Supply Chain Components

The specific components of the supply chain are unique to each type of industry, and within each industry there is variation depending on the chosen method for addressing the service of customers. There are several important steps in the process, and we will deal with the general case first. The high-level view for discrete manufacturers includes elements of the physical flow, including raw material suppliers, component suppliers, subassembly manufacturers, assemblers, and delivery to distribution. There is a counterflow of logical information that includes orders from distribution, synchronization signals to subassembly manufacturers, component suppliers, and raw material suppliers. (See Fig. 9.7.1.)

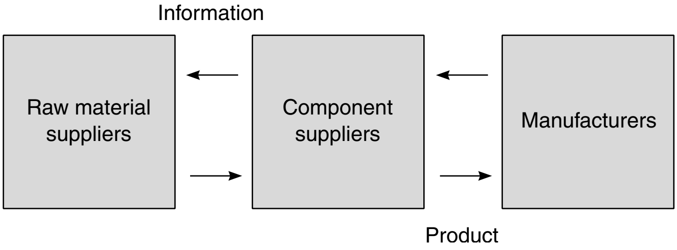

FIGURE 9.7.1 Supply chain information flow.

At some point in the logical flow, most industries will transition from the certainty of the customer order into the uncertainty of a forecast demand. This occurs when customer tolerance for delivery delays is shorter than the overall process time. These transition points define the logical process steps for staging inventory, and they usually define the boundaries between corporations as well. It is at these points that supply to multiple customers may be economically considered as a method to improve asset utilization.

As the new systems technology changes the dynamic of the supply chain process, these new boundaries can change quickly, rapidly driving industry restructuring. This trend is already redefining traditional manufacturing and distribution in several industries. As the use of the new technology is better understood, it is hard to perceive how any industry will remain unaffected.

Supply Chain Trends

The most important trend in the use of supply chain concepts is the introduction of the customer order into the overall equation. The generally accepted practice has been to compile total demand in the forecasting process, then to operate a separate process that attempts to build a master production schedule to satisfy this demand. As actual orders arrive, the product is either available or not available. If product mix changes unexpectedly, the correction occurs in the next planning cycle (usually monthly). The objective of the dual process has been to achieve higher efficiency in the factory by increasing batch size. This batching process is now viewed as too cumbersome to survive the dynamics of the customer trade movement—each customer order must be addressed individually.

Manufacturers must have the ability to immediately assign a promised delivery date to a single customer order in seconds, based on the conditions throughout the supply chain at that instant. Organizations unable to make this immediate commitment will be left behind. It is equally important to then reserve, or peg, the resources and materials to that order to avoid double commitment. Customer-driven order processes also require the ability to manage upsets with ease.

A customer-driven approach cuts across several layers of traditional planning and scheduling processes and integrates business operations around the customer order. While there are still APS systems that serve the old operating model, the transition to the newer APS systems offers such important benefits that the adoption rate is predicted to be faster than for any other new manufacturing technology. The pressures to adopt will be high, and the stakes for delay will be large.

The IE must carefully weigh the overall impact of gravitating to a conventional planning and scheduling strategy. In discrete manufacturing, this usually means a focus on the microview—for example, focusing on workstation setup time, machine utilization, and optimized loading systems. If the manufacturing operation operates far below modern competitive standards, some improvement can be achieved from almost any systematic process. Ultimately, this scenario will result in a need to replace the system a second time to achieve the global view and its concurrent benefits.

Setting Supply Chain Goals

The goals and objectives of supply chain management are straightforward:

- Improved delivery response time and delivery reliability
- Increased, effective throughput
- Reduced systemwide inventory
- Greater stability throughout the supply chain

While most attention to supply chain issues has been focused on inventory reduction, the most important benefits relate to the impact on customer relationships. These customer-oriented benefits likely have more impact on financial performance than any other measure. Unfortunately, the financial benefits of improved customer relationships are not easily measured. With more precise data available on work in process (WIP) and throughput variables, the tendency is to emphasize these benefits.

With this focus, supply chain is not different from the just-in-time (JIT) concepts introduced in Japan in the 1970s and in the North American and European manufacturing communities in the 1980s. The important distinction is that the use of computer technology and the generalization of the operating model have greatly expanded the range and the degree to which they can be applied. It is especially important to note that simple system strategies (such as kanban) have not proven successful in the generalized form. Larger factories with complex product-mix issues have been especially resistant to the simplification techniques. Complex factories require far more sophisticated solutions than can be imposed through the manual techniques of these systems and their computerized counterparts, and this has been the most successful area of improvement for the new technology solutions.

Another concept has begun to permeate the thinking of manufacturing managers as new systems now provide broader capabilities. When implemented with careful analysis and thought, the additional benefits of faster customer response and stronger market position are achieved at the same time. As one manufacturing executive rightly stated, ". . . reduced inventory is a fortuitous accident that occurs when you do manufacturing right." In our viewpoint, doing manufacturing "right" means building business processes to satisfy the customer's needs faster than any competitor.

When approached in this manner, results achieved are the opposite of traditional thinking on the subject. Instead of a supply chain design built on the idea of a forced trade-off between benefits (service level, responsiveness, inventory, and throughput), all of these metrics can actually be improved concurrently. In addition, the reliability of the entire delivery process improves, which in turn reduces the oscillations inherent in all inventory systems. (See Fig. 9.7.2.)

Ultimately, the metrics used to measure the performance of a factory must change. Rather than measuring the factory by singular metrics, there must be consideration of the impact of a supply chain strategy on all of the critical measures. Fundamental to the new supply chain thinking is a new view of inventory as a dependent variable rather than as the primary focus

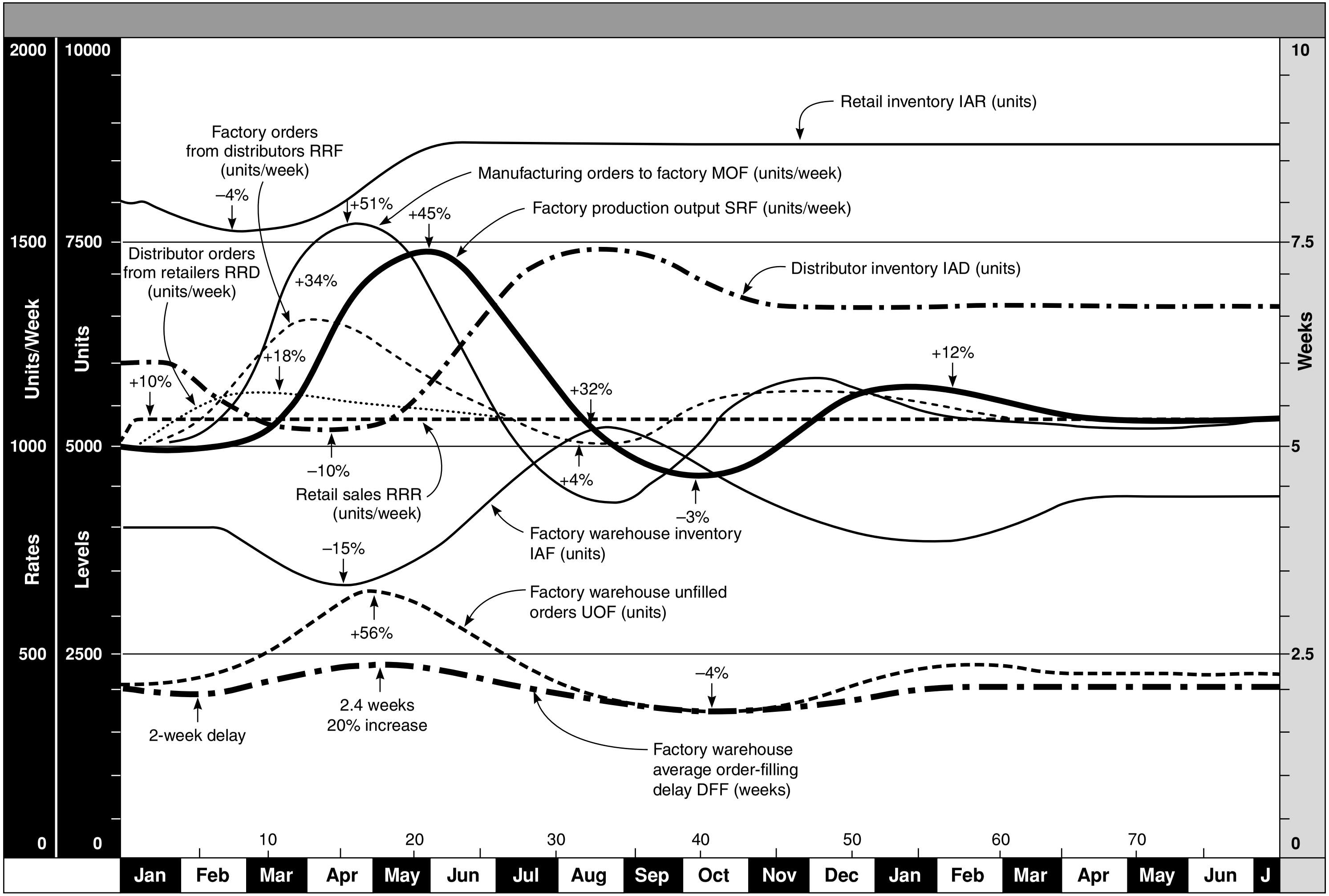

FIGURE 9.7.2 Product-distribution system.

of control. Time becomes the critical determinant throughout most of the chain. Reducing time delays in the process has the concurrent benefit of reducing the inventory plan levels and oscillations.

As each of these concepts is expanded, the approach will be to offer general guidelines rather than specific solutions. The specific approach suffers from the problem of being limited to a single industry, and dealing with all industries would be too large a task for the available space. With general guidelines, it is our hope that experienced IEs will be able to synthesize solutions appropriate to their industries and to the business objectives of their specific enterprise.

THE DYNAMIC BEHAVIOR OF SUPPLY CHAIN SYSTEMS

Recent excitement about the promise of supply chain systems is based on the potential delivery performance improvement, the economic impact of reduced inventory, and the benefits of more effective use of capacity. Investment in inventory and logistics across the entire supply chain is estimated at five to ten times the investment level in the factory. That is why there is so much interest in applying APS and supply chain systems to coordinate the entire flow of material and allocation of resources across the extended enterprise.

The original APS systems were aimed at managing the scheduling problem inside the factory, and they did a fair job of achieving that goal within the limits of the MRP planning paradigm. But because the greater proportion of the problem appeared to lie outside factory walls, attention shifted to the suppliers and to the distribution and logistics chain. This move was premature. The importance of the manufacturing operation to the stability of the supply chain far exceeds the proportions implied by the level of inventory.

Methods of controlling the dynamic behavior of an inherently unstable system must also evolve as the concepts move outward from the large companies who drove the early projects. Most of the early success in this area has come from large companies with near monolithic control of their supply chain. Migration of this type solution to midsize manufacturers is not likely soon—they do not control the supply chain, so a qualitative change in system strategy will be needed. A new movement is emerging in both the United States and Japan to build this new model, and the distributed multisite operating model is emerging as the preferred approach.

Supply Chain Inventory

Inventory levels in most supply chains are excessive. For years, there has been an assumption that the underlying cause of this inventory excess was the result of forecast error. And for an equal time, the ideal of a pull system driven only by customer orders was offered as the solution. But this given ideal model was wrong. Figure 9.7.2 shows what happens in a pure pull system (*pull* meaning order-driven). In this system there is no forecast, so there can be no forecast error. A one-time 10 percent increase in customer order rate causes a 15-month upset in the supply chain. Within five months, the surge has been amplified fivefold at the factory. The system is clearly unstable and demands much higher levels of inventory than are warranted by consumer demand alone. The information time delays, which are the root cause of these oscillations, are substantial between points of the distribution system. Many supply chain systems are still built on these timing parameters 40 years after the inherent problems were exposed. This natural system behavior is the same for systems inside the factory as well. Any sequential communication system exhibits this behavior. Kanban is an example of a sequential system where the additional constraint is added to limit the amount of inventory possible in the system. In this case, the effect is to produce a truncated oscillation of the inventory quantity, but to then produce a related shortage condition described as a "wave of starvation," which completes the cycle. These oscillations are greatly detrimental and are to be avoided to the greatest extent possible.

AN INTRODUCTION TO SUPPLY CHAIN MANAGEMENT

Based on this view of supply chain inventory, the conventional method of correcting forecast error by adding inventory and freezing more schedules will make the system worse, not better. The higher inventory and larger batch size (longer delay time) result in more violent oscillations.

Supply Chain Oscillations

Time delays in a sequential communication process lead to system oscillations. Once the process is designed, a natural set of operating time delays exists, which translate to a natural level of inventory and a natural period of oscillation in the inventory. Changes in product mix and timing cause a more complicated picture. Any attempt to directly control the inventory levels (kanban, two-bin system, etc.) all result in starvation problems under unstable conditions. The inventory is inherent in the system once the timing parameters are established. During the supply chain design process, careful attention to time delays is essential. Minimizing these delays reduces the magnitude of the oscillations.

Figure 9.7.3 shows an example of several simple oscillation patterns and the effect of changing the delay time through the system. When the delay time is halved, the amplitude of oscillation is also halved, while the frequency is doubled. While it is unrealistic to eliminate the oscillations entirely, it is possible to convert them to a more manageable state.

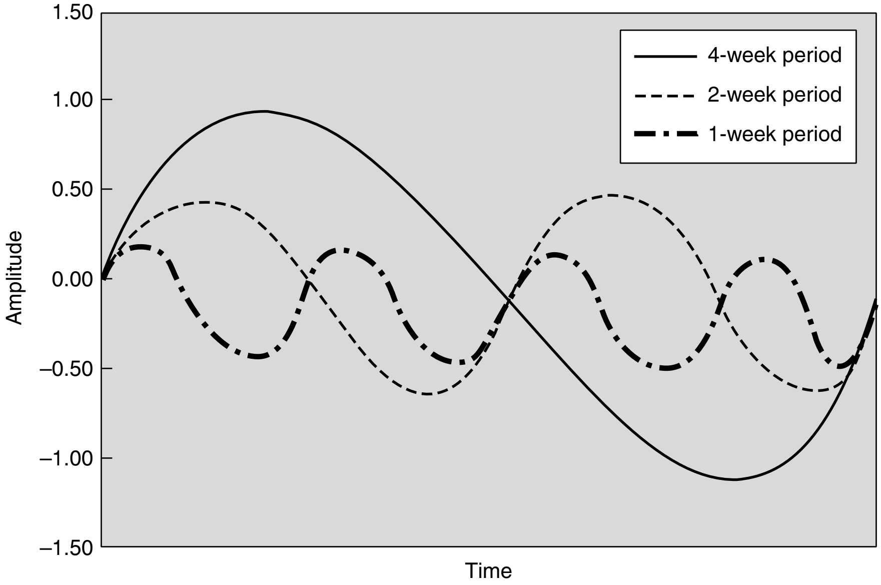

FIGURE 9.7.3 Variable time delays.

Controlling System Dynamics

If the oscillation magnitude is a function of time delays through the system, then the use of broadcast communication is one way to eliminate the inherent delays in sequential systems. Figure 9.7.4 shows the comparison between sequential and broadcast communication.

In the broadcast mode, changes are communicated to all parts of the supply chain concurrently, with appropriate time phasing. When this form is feasible, it is always the best solution because all parties (operators in the plant and suppliers) are working on the same set of priorities. Change is communicated and responded to in a coordinated fashion.

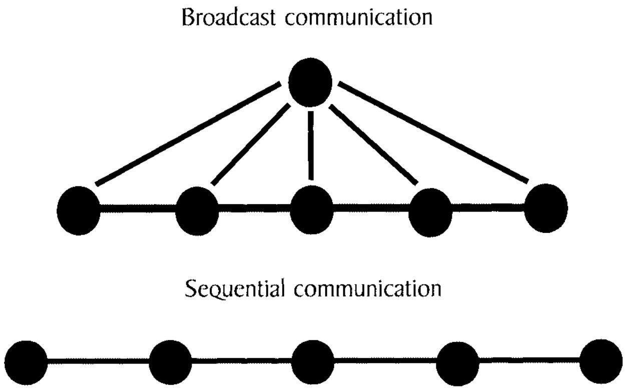

FIGURE 9.7.4 Broadcast communication benefits.

The ideal of broadcast communication can be achieved only where the production cycle across the entire supply chain falls within the customer's delivery time expectations. In cases where this is not possible, the reduction of communication time delays is crucial to a stable operation. In these cases, the sizing of inventory buffers and the replenishment method will also be important (see Inventory Management later in the chapter). The conventional operating mode of sequential communication is not a particularly useful model despite its widespread use.

The control of system dynamics is equally important inside the factory. The internal flows through the factory represent the same sequential communication chain that was discussed for the supply chain. The factory environment is more complex because of the conversion processes inherent in manufacturing. Oscillations and out-of-phase activities are even greater risks in this complex environment. In fact, it is impossible to operate an effective supply chain unless the performance of the factory is responsive and reliable. To achieve this goal, the lead time through the factory must be kept to a minimum. Systems must be able to accurately calculate the required launch date to achieve the expected delivery date. When that launch date is calculated, it must also take into consideration the potential collisions in the competition for factory resources.

For a supply chain that is completely controlled or dominated by one company, a broadcast communication strategy can work well. But for midsize manufacturers, in many cases, suppliers and distributors are bigger than the manufacturer itself. In these cases, the second option of reducing time delays through faster communication can be effective. The use of electronic data interchange (EDI) technology is one example, but the solution could also be as simple as sending a daily fax of orders rather than weekly or monthly. The new model for this multisite supply chain using instant communication will be discussed in a later section of this chapter.

Factory Response

Factory response time is not as easily modified as has been believed for the last 50 years. Our preferred measure for factory responsiveness is the *makespan ratio.* This metric looks at factory lead time as a multiple of the productive hours of work needed in manufacture. This measure allows factories of different types to be compared. Typical discrete manufacturers operate at makespan ratios of 20:1 or 30:1. Some are as high as 200:1. It is typical for a world-class manufacturer to operate at levels of 3:1 [5].

Figure 9.7.5 shows the time-delay structure for a typical manufacturing facility. Start with the assumption that the sum of all the cycle times throughout the facility is one day. A typical

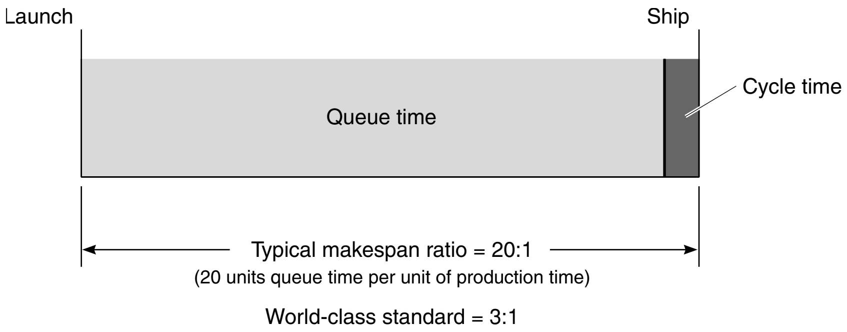
Launch
Ship
Queue time
Cycle time
Typical makespan ratio = 20:1
(20 units queue time per unit of production time)
World-class standard = 3:1

FIGURE 9.7.5 Factory makespan time.

factory operation will then require 21 days of total makespan time, with the additional 20 days being spent in queue time. World-class manufacturers have universally focused on eliminating time delays to achieve the 3:1 standard.

This faster-responding operating model has multiple benefits. First, since the launch of an order into the factory can be delayed until four days before delivery, a greater proportion of the demand is known with certainty. Therefore, the forecast error has been minimized and the capacity is more likely to be used to produce something that the customers want to buy. Second, with the shorter delay time through the factory, the remaining forecast error is corrected more quickly, thereby reducing the magnitude of the oscillations.

Thus, the situation is controlled by the factory dynamics, even though most of the inventory is elsewhere. Inside the factory, the amount of time required to process an order greatly exceeds the actual work done on the product. This situation is amplified across the entire supply chain. Reducing this ratio has the largest favorable effect on the supply chain.

Local Efficiency and False Optimization

Many operations that suffer from poor makespan ratios achieve high levels of local efficiency. Any attempt to focus efforts heavily on local efficiency, including most optimization strategies, will result in a degradation of the makespan ratio metric. The result is longer delay times and more buffer inventory. A focus on local optimization strategies has led to serious suboptimization of global objectives in the factory. These false optimizations are based on the incorrect assumption that locally optimal solutions can be accumulated into a globally optimal solution. This premise is known to be incorrect and has been the subject of numerous dynamic modeling efforts. The secret is in picking the right metrics, then modeling in a way to show the enterprisewide effects.

First and foremost, the prime directive of any manufacturing organization must be the timely delivery of customer orders. Do not confuse profits, efficiency, utilization, or other internal management metrics with this prime directive. If the prime directive is not met, all other metrics will rise only in the short term—and the enterprise will fail in short order. When examples of higher machine utilization through setup reduction are proposed, it is rarely presented in the context of the damage done to customer deliveries. Since higher inventories are required, the system becomes unstable, requiring even higher inventories. This inventory represents queue time, which causes response delays. All world-class supply chain strategies have aggressively addressed this problem.

When analyzing the impact of strategy on the supply chain, step back and find the real measure of merit for the entire system. It should be the utilization of total assets employed in the timely delivery of customer orders, not machine utilization, burden absorption, work-in-progress reduction, or anything else. It is asset utilization, as measured by the *capital intensity ratio* (total capital employed to sales revenue).

APS AND SUPPLY CHAIN MANAGEMENT

As stated in this chapter's introduction, the most important benefit of supply chain management is the strengthening of customer relationships. APS, with its ability to instantly deliver a realistic plan and therefore deliver on time to the customer, is a key driver in this ultimate supply chain goal.

Is it possible to properly manage a supply chain without APS? Since it has been done for several millennia, the official answer must be yes. But in the highly dynamic world of customer trade, the past methods of managing the supply chain based on batch process and periodic revision of a static plan will result in noncompetitive performance. All of the market research observers on the scene now agree that APS will play a central role in supply chain strategies and that the dynamic model will predominate.

APS is probably the fastest-growing segment of the enterprise applications market, with a compounded annual growth rate exceeding 70 percent (AMR Research). It can change, and indeed, already has changed, the way that manufacturers service their customers and interact with other members of the supply chain.

APS describes a growing number of planning and scheduling applications designed to improve both responsiveness and operating efficiency. But only a few of these systems deal with the issue of the customer order and its dynamics while improving efficiency. APS develops realistic, synchronized production plans and schedules based on real-world factors. The newest system designs combine supply chain planning, enterprise planning, production scheduling, and available-to-promise and capable-to-promise technologies to enhance customer responsiveness and delivery accuracy, to reduce inventory and manufacturing costs, to provide flexibility to meet competitive challenges, to improve makespan ratios and resource utilization, and to significantly improve financial performance. (See Fig. 9.7.6.)

Another way to explain APS is to contrast it with traditional planning, or MRP, which is a step-by-step sequential planning process. In this process, material is planned without regard to capacity constraints, then the capacity plan is devised. But the MRP process is often not as streamlined as the designers intended, resulting in a top-down, single-direction process involving many potential restarts prior to resolving the final plan. When the process is started, the planner must create a master production schedule, then a rough-cut capacity requirements plan, then material requirements and capacity requirements plans—with validation required at each step of the process. During this lengthy process, adjustments made to accommodate capacity problems may cause material problems and vice versa. The nature of this process is that it must operate in batch mode and not very frequently.

APS, by contrast, plans all materials and capacity resources at the same time. Each step of the planning process and each level of the bill of materials is completely planned simultaneously. And the process operates at the customer order level so the dynamics of the real world can be accommodated. Changes in product mix in the incoming orders can be immediately detected and corrected.

APS uses a finite-capacity or constraint-based approach, meaning the plan will not overcommit manufacturing resources beyond available capacity. Because resources are planned at the same time as materials, there is no need to make unjustified assumptions about resource availability. Each activity is fully planned and coordinated with other demands on work centers, people, machines, and so forth to generate schedules that are based on reality, not on fixed lead-time estimates and cavalier assumptions about resource availability. Flexible, not static, data is used to build the plan.

Exploiting recent advances in computer technology, the APS planning cycle is typically carried out immediately—and measured in minutes or even seconds—as opposed to being

AN INTRODUCTION TO SUPPLY CHAIN MANAGEMENT

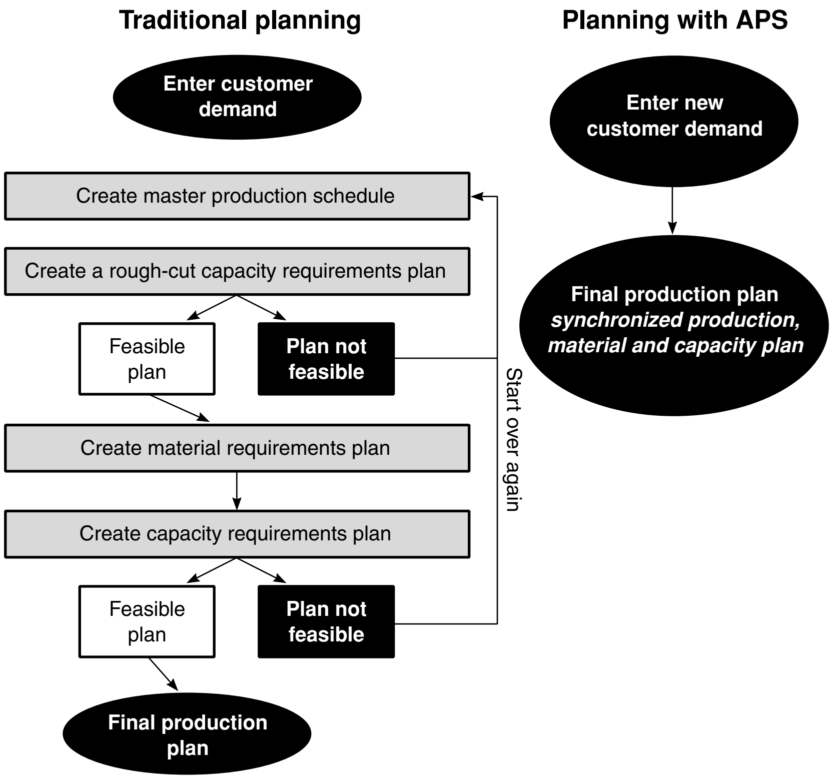
Traditional planning
Enter customer demand
Create master production schedule
Create a rough-cut capacity requirements plan
Feasible plan
Plan not feasible
Create material requirements plan
Create capacity requirements plan
Feasible plan
Plan not feasible
Final production plan
Start over again
Planning with APS
Enter new customer demand
Final production plan
synchronized production, material and capacity plan

FIGURE 9.7.6 Traditional planning and planning with APS.

generated slowly after business hours or over the weekend. The significance of this point is that planning now becomes a decision support tool, not simply a reporting and analysis tool. Resource availability questions can be answered, alternatives immediately explored, and the impact of disruptions—and your proposed solutions—can be identified without delay.

The Scope of APS

The term *APS* actually denotes a number of planning- and scheduling-type applications, and there are many different approaches to APS for different manufacturing environments. However, the approaches may be grouped into four primary methods. These are network-based models, threaded network–based models, finite-capacity schedulers, and optimizers.

The term *network* is used here to describe the model of multiple customer orders threading their way through the factory. It is similar to the use of the term in critical path networks. Do not confuse this with the computer network that these systems use in their operation.

Network-based models have the ability to resolve global priority issues, anticipate bottlenecks, and synchronize customer orders, all without relying on queuing. Starting with the customer order, the systems build, then resolve, a deterministic network of real-world paths that the order must travel for production—totally synchronizing the facility for each component and part required for production and supply. These systems adapt quickly to change.

Threaded network models are the logical extension of, and conclusion to, network-based models. These systems add three requirements to the definition of APS: (1) operates at the customer-order level through the entire bill and route; (2) provides continuous synchronization at the customer-order level; and (3) provides launch control at the operation level to ensure that execution matches the plan. Threaded network systems recognize that the dynamics of customer-centric, real-world operations are constantly changing.

Finite-capacity scheduling (FCS) systems are mostly simulation-based models, although some use math modeling. These systems originated with the assumption that the MRP system would produce work orders and the FCS system would fit the jobs into its existing capacity. Because it assumes the MRP paradigm, it forces manufacturers into batch mode, working across one level of the bill at a time. FCS helps manufacturers achieve workstation capacity utilization, but lacks the capability to make global decisions. By focusing on the work-center view, the global objectives are always compromised, including the synchronization of capacity and material and the performance against customer dates. As the MRP technology is replaced in the enterprise systems, the use of FCS technology will also decline. Because these systems were the first APS-like technology (c. 1980), they represent a rather large installed base.

Optimizers produce factory schedules that fit the existing factory structure, and these have been primarily successful in process industries, where production is inherently batch-oriented. An optimizer system can help manufacturers achieve the optimal balance between productive yield and timely delivery, but this balance becomes invalid as soon as a change occurs during the plan period. Optimizers work well for continuous-process, batch-mode manufacturers with static environments, stable schedules, and no discontinuities. Optimization technology is severely limited in order-centric, dynamic environments.

Benefits of APS

All four of the aforementioned systems can be implemented with some form of order promise capability, but some are inherently better than others for the support of this capability. It must be emphasized strongly that accurate order promise is critical to success. No amount of clever scheduling can overcome the damage done by inaccurate, unrealistic promise dates.

The benefits of APS go beyond better plans and schedules and include increased customer intimacy and service, reduced inventory and manufacturing costs, and measurable financial results. As described earlier, APS technology reduces information delays to a minimum. This makes the system more stable than any other approach and causes the concurrent benefit of better customer responsiveness with reduced inventory. When applied in the supply chain context, only the network-based and the threaded network architectures can deliver these benefits for discrete manufacturers. In batch-process and continuous-process industries, any of the four technologies can be applied as long as there is a careful assessment of the match to the business objectives.

ORDER PROMISE

The most important function in supply chain operations is establishment of the customer order target delivery date. This target date is usually referred to as the *promise date.* If the order flow on a new order can be established with certainty at the time of order entry, the most common factory disruption, accepting a new order into an already loaded schedule, will be eliminated.

In most cases, the order promise function occurs as a part of a sales/negotiation process with the customer. Some business contracts require a fixed order response time. In either case, the game has changed. A wealth of information on goods and services, including price, options, and delivery, is now directly accessible for your customers. An immediate understanding of the effects of accepting a new order must be known instantly, or a continuous disruption to the manufacturing plan is inevitable. This has driven a change in the view of the functions of APS and supply chain systems that support order promising. Available-to-promise (ATP) functions

AN INTRODUCTION TO SUPPLY CHAIN MANAGEMENT

that peg against finished-goods inventory or production plans are no longer considered adequate. The new promise test is called capable-to-promise (CTP), and it looks at multiple levels of the supply chain, typically in this order:

- Finished-goods inventory
- Manufacturing capacity
- In-process intermediate inventory
- Make-versus-buy decisions on intermediates
- Subassembly and component delivery lead time
- Raw material inventory

With the ability to provide the best nondisruptive delivery date, it is now possible to immediately understand when a customer request will cause a disruption to the existing schedule, thus delaying other orders.

An equally important step in this supply chain operating model is to immediately reserve the materials and capacity necessary to ensure that the order promise is met. This form of pegging, sometimes known as *hard pegging,* has fallen out of favor over the last decade because of its perceived inflexibility. But there are signs of renewed interest with the advent of the ability to rapidly repeg when inevitable upsets occur. The advantage is the ability to avoid double commitment of the materials and resources.

Caveats on Order Promising

There are several pitfalls to avoid in the review of the business process surrounding order promise. In the past operating model, most of these issues have been solved by longer makespan times, allowing manufacturing time to figure it out. This operating model will not survive the next technology shift, so the issues must be revisited.

Guaranteed Delivery Response. Not all promise dates are negotiated with the customer on an order-by-order basis. In a business environment where there is no flexibility in order promise (fixed lead-time promise is in place), there is substantial risk of disruption. In some rapid-replenishment-to-retail models, the orders from large customers are contractually required to be delivered in a very short time. This means that the business must be willing to break a delivery date promise to another customer or must have available capacity on standby to satisfy surges in demand. The attempts to buffer surges with inventory have been ineffective except for very simple products. For an increasing number of manufactured goods, it is now recognized that the total capital required for standby capacity is often lower than the capital cost for inventory. While there is no generalized rule on this issue, be aware that the most common assumption of the last several decades—inventory is cheaper than capital—should be challenged and confirmed before a business strategy is adopted around it.

CTP and Multisite Order Promise with APS. All four of the APS systems described earlier can be implemented with some form of order promise capability. But some operating models are inherently better than others for the support of this technology.

In batch mode systems, the most likely approach is a separate add-on module that attempts to approximate the nondisruptive date for the order. Especially in the case of the optimizers, the second step in the process is to break the existing order promises by finding a better solution to the mathematical problem. These approaches should be applied where there is minimal pressure on promise and delivery accuracy.

The network systems have the ability to make precise order promises and to immediately reserve the materials and resources necessary to deliver on the promise, thus avoiding the double-promise syndrome. While it is possible for these systems to operate in a mode similar to the airline reservation system, not all network-oriented systems will be implemented with this dynamic. For operations where promise date accuracy and delivery-to-promise are important business considerations, careful understanding of the order promise mechanism of the supporting system is an urgent requirement.

Multisite Supply Chain Operation

In the quest for more rapid response in the execution of orders, there is the beginning of a new view of how the initial order promise function operates. Figure 9.7.7 shows a generalized model for the integration of the entire supply chain with the logistics and distribution operation.

The messaging architecture assumes that each facility has a functioning APS system with the capability for real-time CTP communication in a compatible protocol. When the system has the ability to manage recursive date requests at a site, the make-versus-buy decision can be executed in real time while the date request process is in process. With this generalized model, the sites can be manufacturing facilities, distribution warehouses, or distribution sites with light assembly. The important change in this model is that there is no longer a distinction between the upstream supply chain (manufacturing site and its component suppliers) and the downstream distribution (distribution and logistics). In the operation of this model, the best date (or the best date at a competitive price) will get the business. Whether used to support customer trade or in the more conventional operating model of load balancing across multiple manufacturing sites, this capability changes the core assumptions on how to manage the supply chain.

INVENTORY MANAGEMENT

There are a vast number of inventory management schemes used today. Most are accompanied by information and industry myths that combine to make the design of the inventory management process murky at best. This section will provide some structure to the analysis process and will help isolate the myth and misinformation from fact.

The reference of most general applicability for the in-plant inventory management options is *Factory Physics* [2]. It is probably the most complete work on inventory methods. Unfortu-

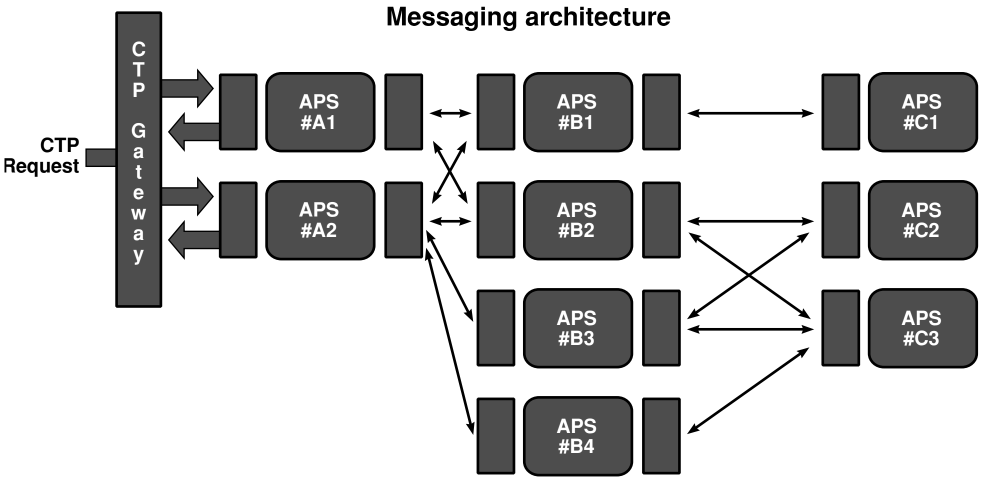

FIGURE 9.7.7 Multisite promise dates.

nately, there is no corresponding work extending this effort to the supply chain in its dynamic high-response mode.

It is important to remember when discussing inventory management principles that there is no one set of practices that fits all conditions and that inventory management is fundamentally about time management rather than the management of quantities.

Since each business has unique needs in the application of inventory management, the view here centers around basic design principles rather than specific solutions with limited applicability. IEs must have a broad view of the process, not just the plant-level perspective. A solution that merely moves inventory from one location to another may only trade inventory investment dollars for higher purchase material expense because someone else is holding the inventory.

There are four reasons to have inventory in a process:

- *Process-related.* (1) Process variability (primarily yield) and (2) batching strategies (to increase utilization of equipment)
- *Customer-related.* (3) Lead time compression and (4) time shifting of capacity loads (seasonal variation)

One of the prevalent myths is that pull systems (order-driven) are better than push systems (forecast-driven). The corollary misconception is that forecast error is the cause of all inventory problems. Both concepts are wrong. Pull systems are unstable even in the face of zero forecast error. The nature of customer demand is that it is unpredictable, so the forecast will always be wrong. Thus we come to the first principle of inventory management: *The forecast is always wrong.* The important consideration is not how to make a perfect forecast, but how the entire system reacts to the inevitable forecast error. The second principle provides guidance on this critical issue: *The longer the forecast error is undetected and uncorrected, the more violent the required correction.* When these concepts are combined, the motivation for the new supply chain concepts becomes clear. The objective is to reduce the number of sequential communication points in the process (reduce the oscillations of Fig. 9.7.2) and to minimize the time delays of information propagation through the process (decrease the amplitude of the remaining oscillations as in Fig. 9.7.3). Wherever possible, the process should be converted to broadcast communication whereby the entire supply chain is informed of changes in priority concurrently.

The broader view of the supply chain is also leading to the conclusion that all processes are a combination of pull and push systems. The only true pull signal comes from the end user/customer. And no consumer product can move from raw material to end-user consumption within the time frame expected by the customer. The introduction of customer trade and the Internet changes the rules further—the best delivery available worldwide is now the norm required by the customer. In this environment, previous attempts to solve the problem in pieces were, and still are, inadequate. Most of these strategies merely moved the inventory somewhere else, with no net improvement in the dynamics of the system.

When inventory management strategies are discussed, the reality of the position in the supply chain should be considered first and foremost. Second is whether the proposed change in business process reduces the total time delays through the system. If systems like JIT or kanban are applied without changing the sequential nature of the information flows or the timing and responsiveness of the flows, no net improvement will be realized. The use of APS and supply chain systems technology eliminate the deficiencies of the fixed or manual systems and offer real benefits for manufacturers. However, these systems do not eliminate the dynamics of the process. Thus it is possible to apply the APS technology in ways that merely emulate the existing system, and no improvement will occur.

In the supply chain there are two demand-related inventory-staging processes that are sometimes confused. The first is the process of staging inventory in the supply chain to satisfy later demand. Examples include the seasonal production plan for items like film, greeting cards, or beer. The objective is essentially time-shifting the production to a different period of the year. The second is the use of buffer inventories to compensate for a mismatch between customer delivery expectations and supply chain delivery time. An example is the PC business, which stages subassemblies near the end of the process and assembles the final product only after the receipt of a customer order. These two cases represent opposite ends of the spectrum of inventory management problems and serve to highlight the growing importance of supply chain management.

The seasonal adjustment process attempts to use slack off-season capacity to get ahead of excessive in-season demand. Here the forecasting process is the driver, and real-time dynamics are less important.

In the case of buffering lead time, the real-time dynamic is critical, because buffer inventories can easily be depleted by a surge of demand, and quick response is the only defense.

While the methods used to address these two cases will be quite different, there are two key points of commonality that can illustrate supply chain principles. The debate in designing a supply chain strategy is centered around one of the following issues:

- Where in the process to stage the inventory
- How to ensure quick response when the forecast error is known
- Which method of inventory replenishment to use

The important change introduced by supply chain strategies is the recognition that most conventional inventory management schemes are very weak in addressing the needs of the customers and in effectively using the financial assets of the company. It is only with the introduction of the computerized supply chain systems that new operating alternatives become available.

In designing an inventory management system, the first step must always be to decide where the inventory will be staged. The staging point in the large-process view should consider the degree of product complexity and the response to demand; reacting earlier in the process offers more flexibility and lower cost, while later in the process is more responsive to customers. Most supply chains have obvious staging points, and the structure of the industry tends to reflect these timing and economic realities. But again, the introduction of high-response computer systems that span the supply chain have changed the landscape. Whereas the norm for communication along the supply chain was measured in weeks or months when Forrester wrote his groundbreaking work in 1961, today the delays are measured in days and, in the best examples, minutes. So staging points need to be continually challenged and reviewed.

One of the significant changes in the application of systems technology is the decline in the use of systems based on queuing theory. This body of theory has been popular for decades because it allowed a convenient method for modeling complex systems. But the introduction of network systems has begun to expose a weak spot in the use of queuing theory systems in operating roles. They only work well with queues. Attempting to apply these strategies to the order-driven environment of the modern supply chain has been counterproductive. In a few cases, high-capital-intensity industries have continued to use queuing strategies successfully because of the lack of competitive pressure to change. A new generation of hybrid systems that uses the network model to dynamically link operations to the customer demand is now available. These systems achieve both the utilization desired in capital-intensive industries and the demand dynamic required of modern supply chains. The effectiveness of these systems looks promising, but the experience base is still thin.

THE ROLE OF INDUSTRIAL ENGINEERS IN SUPPLY CHAIN MANAGEMENT

The supply chain vision is one of complete coordination. Incoming materials, factory operations and downstream distribution must all be highly responsive to customer demand shifts and carry no excess material. Information technology, such as EDI, standardizes and speeds communications. Scheduling and coordination are predicated on constraint-based algorithms that take into account the factory limitations. In this model, all the traditional time delays are taken out of the communication stream, and delivery expectations are coordinated and met routinely with minimum cycle time delays.

But the message is easier to describe than deliver. The system that can meet the demands of the vision is extremely complex, as IEs will recognize. The model of rapid response and minimum inventory is much more difficult to implement when the supplier base has many options and demand flows span complex manufacturing operations. The complexity of supply chain relationships continues to be overlooked by many software developers.

With most of today's implementations, the system does not consider the internal dynamics of the factory, the driving variables of the oscillations described by Forrester, or the relationship between planning and execution. Most early MRP system implementations made the problem worse, and today's MRP/ERP implementations aren't doing much better. Even today, most MRP and ERP systems have a high probability of destabilizing the operation. Without addressing these core issues, the supply chain initiatives will also succumb to mediocrity or failure, though the impact is likely to be larger and more visible.

Despite the difficulty, the vision of a business system integrated from suppliers through the factory and on to customers is too powerful a siren song to go away. But the trip from vision to reality follows a very rocky road. As the pitfalls of the new supply chain strategies become more broadly understood, a new role will emerge, demanding very specific skills already possessed by IEs. These skills include the following:

- Thorough understanding of sequential and dynamic systems
- Skill in using dynamic simulation tools to test business operating models
- Familiarity with the systems and the methods of correcting unstable dynamic systems
- Understanding the practical limits of flexibility and synchronization in the factory

Expanding these skills to a new environment with new demands, however, will require addressing an increased dependency on information technology and IT design. Another new challenge is getting the organization to function in a horizontal (rather than the traditional vertical) manner. Departmental organizations tend to focus on satisfying the boss rather than satisfying the customer, because the information and reward structure tend to work up and down the chain of command. A business and business system focused on order fulfillment is a new way of organizing this horizontal view, but now it becomes dependent on an integrated information view.

Evolving Role

The traditional activity of IEs in manufacturing has been focused inside the factory. As discussed earlier, the factory will remain a key link in the supply chain. But the IE role will expand to address the entire supply chain, including multiple organizations. The emerging business strategies suggest it will now expand to include multiple organizations.

Factory synchronization and capacity balance are still key to the success of customer service and factory efficiency. Even in the integrated supply chain strategy touted by the gurus, the failure of the factory to deliver on time can break down the entire supply chain process. Incoming materials pile up and downstream deliveries are unmet. Since all supply chain strategies include an inventory-reduction objective, the system becomes more susceptible to the upset of broken deliveries. Now the role of the IE in synchronizing the factory is even more crucial. Only a synchronous operating model can support the combination of rapid response and predictable deliveries in an environment of reduced inventory and capacity buffers. Without success in order flow synchronization, supply chain initiatives will fail.

The IE function normally is considered a service group within manufacturing operations. The normal operation has been a want-and-response model. Before IE concepts are accepted broadly in supply chain initiatives, senior management must replace this limited view of the IE function. IEs shouldn't wait for empowerment—the first move must come from the IE community.

The tools will be familiar to the trade. Dynamic discrete event simulation will be the only effective tool for testing alternative supply chain designs. Furthermore, the risk of unstable information flows requires this approach to include information dynamics as well as material flows. IEs will need to be involved in new ways in major information systems development. While crucial to the success of major system operation, it is rare to see dynamic simulation used early to eliminate costly mistakes in design activities. This oversight needs to be remedied.

Most problems with today's software and consulting strategies stem from a simplistic view of today's factory dynamics and related inbound/outbound logistics. This error stems from systems initiatives being championed by software experts who have only a passing knowledge of real factory theory and practice.

Building aggressive corporate structures like supply chain management is too important to be left solely to the software and business process reengineering (BPR) experts. This is a business process of immense potential. Success hinges on the realistic assessment of the complexity involved and the application of known IE methodologies to devise robust solutions. It will be up to the industrial engineering community to take the initiative in making sure that the strategies are a positive economic contribution to the extended manufacturing enterprise.

CONCLUSIONS

New technologies have made important changes in the approach to supply chain operations. First there is the quest for increased speed as an operational improvement. Second is the competitive requirement for improvement in setting and meeting customer expectations. And third is the recognition of the drastic change in the competitive environment caused by the Internet and the new operating technologies designed to take advantage of it.

The full impact of these changes probably won't be clear for another decade. What is clear today is that our earlier attempts to solve these operating problems through simplification are not now competitive. Customers have access to competitors willing to solve the complex problems in real time. This environment will make the dynamic operations discussed here the norm.

As businesses move forward into these increasingly sophisticated supply chain strategies, technology will be the only method of survival, for both manufacturing organizations and IEs.

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BIOGRAPHY

John Layden currently serves as vice president of supply chain market development for Frontstep, Inc. He served as president of Pritsker Corporation prior to its acquisition by Symix

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in late 1997. Layden's career includes 15 years as president and CEO in manufacturing software, as well as 22 years as an engineer and operating executive with three Fortune 500 manufacturing companies. He is one of the rare participants in the APS industry who learned about APS needs as a plant manager and has been described as one of the "founding fathers" of the APS industry. Layden, who has authored over 40 articles on both the theory and practice of manufacturing systems, speaks worldwide on the subject. He holds a B.S. degree in electrical engineering from Purdue University and an M.B.A. from the University of Wisconsin.

Source: MAYNARD'S INDUSTRIAL ENGINEERING HANDBOOK

CHAPTER 9.8

PRODUCTION SCHEDULING

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This chapter discusses scheduling of production in environments of discrete manufacturing (i.e., production of specific items in discrete lots or batches). Quantitative methods appropriate to other environments, such as continuous flow or process industries, are covered in other chapters.

Scheduling is placed in the context of manufacturing planning and control. It is distinguished from planning. The process of finite-capacity scheduling, using state-of-the-art techniques such as computer simulation, is described, and the integration of a scheduling system with planning applications is explained. Prioritization of production orders under conditions of capacity constraint is discussed. Practical advice is given for the effective use of scheduling to execute the mission of production control. Specific ways that mastery of scheduling contributes to competitive performance are enumerated, and a case study is included.

MANUFACTURING PLANNING AND CONTROL

The industrial engineer's work of designing a plant's manufacturing process involves design of both *production processes* (equipment, flow, capacity) and *infrastructural processes* (planning and control, organization, quality). While it seems obvious that an infrastructure compatible with the production mission is essential for optimum results, a significant number of manufacturing facilities are impaired by unsuitable infrastructures, especially in regard to their manufacturing planning and control functions.

Manufacturing planning and control consists of a set of logistic functions that support the timely and effective processing of production operations. A general design for an integrated manufacturing system is shown in Fig. 9.8.1. This model, or an appropriate variant, applies to a wide range of manufacturing environments. Master production scheduling and material requirements planning may be *lot-based* for discrete manufacturing or *rate-based* for repetitive production. Techniques of capacity planning and production scheduling will also vary with the production environment.

Just as the use of computers throughout industry in the last third of the twentieth century energized the most profound transformation of manufacturing since the Industrial Revolution, so has information technology shaped the transformation of manufacturing planning and control in the last quarter of the century. Computer systems and the proliferation of commercial software made feasible the timely processing of planning and control functions, enabled their integration, and brought them into the practices of manufacturers of all sizes and types. Techniques of planning and scheduling discussed here are computer-based and are available in commercial software.

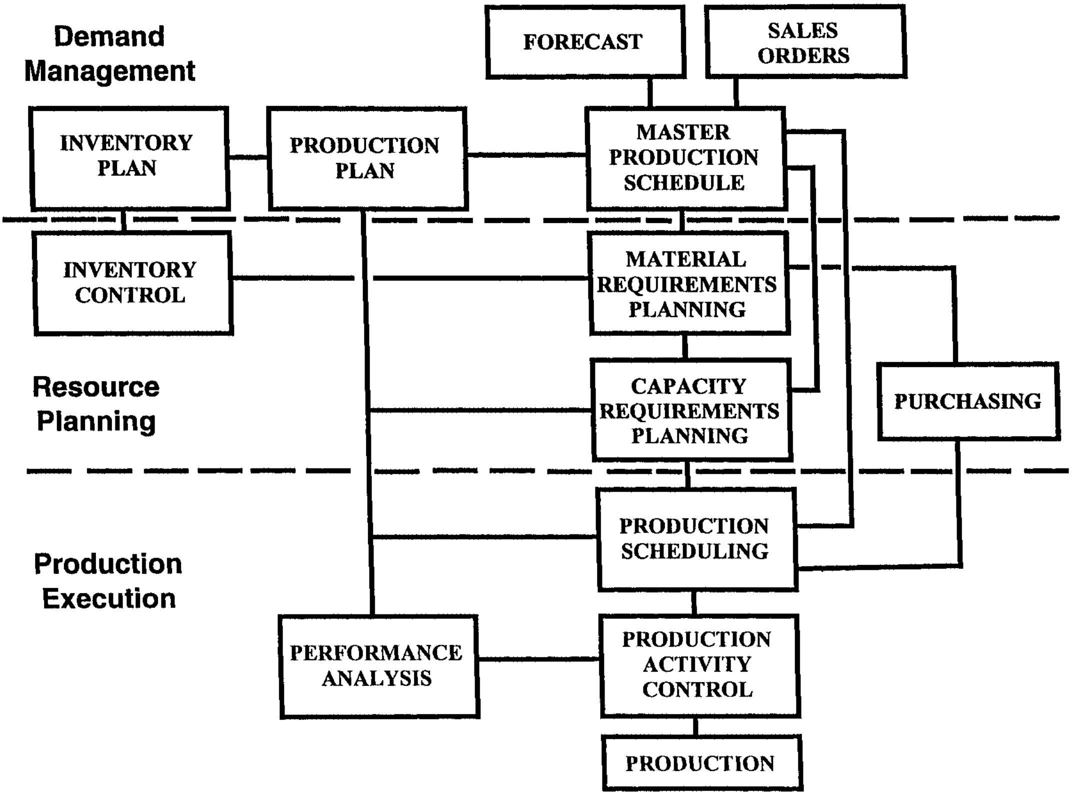

Demand Management
FORECAST
SALES ORDERS
INVENTORY PLAN
PRODUCTION PLAN
MASTER PRODUCTION SCHEDULE
INVENTORY CONTROL
MATERIAL REQUIREMENTS PLANNING
Resource Planning
CAPACITY REQUIREMENTS PLANNING
PURCHASING
Production Execution
PRODUCTION SCHEDULING
PERFORMANCE ANALYSIS
PRODUCTION ACTIVITY CONTROL
PRODUCTION

FIGURE 9.8.1 Integrated manufacturing system. *(Reprinted by permission of Manufacturing Management Systems, Inc.)*

WHAT IS SCHEDULING?

As can be seen in Fig. 9.8.1, some of the functions of an integrated system support production *planning* (notably, those designated *demand management and resource planning*) and some support *execution* (notably, those designated *production execution*).

Scheduling is the centerpiece of the production execution infrastructure. Its most basic purpose is to determine when production orders will be executed. The process consists of determining times for the execution of production activities, then reconciling the schedule with the production plan, and finally supporting decisions and actions to achieve desired production objectives. Therefore, the definition of a *schedule,* as applied to manufacturing operations, is "the specification of future times for execution of production events."

Because the essence of an integrated manufacturing system, such as that shown in Fig. 9.8.1, is the interaction and interdependence of its elements, the function of scheduling cannot be described without consideration of its relationship to planning functions.

PLANNING

Two of the principal planning functions, master production scheduling (MPS) and material requirements planning (MRP), are described in Chap 9.9. The master production schedule states the desired plan for production to accommodate expected demand. Using product bills of materials, material requirements planning provides a time-phased, level-by-level procurement plan (i.e., items to be purchased, items to be made, and times when these things are needed).

It is essential to the planning process to assess the work requirements that have been committed in the master production schedule. This is done by capacity requirements planning (CRP), which plans the elements of lead time of each production order (either actual or planned) and time-phases the production activities of each order over its planned lead time. These elements of lead time are both operation times (setup and run times) and interoperation times (planned allowances for normal move and queue times). When operation times for all future production orders are time-phased for individual work centers, the resulting projection shows the amount of production resources that will be required in each time period in order to manufacture *within their planned lead times* those products planned in the master production schedule. It is not unusual for this projection to show that production resources in excess of planned capacity may be required in one or more work centers and time periods. This means, of course, that either resources must be adjusted or else some products will not be produced as planned.

It is important to understand that the time-phasing of production activities just described is *not* a schedule. It is a plan, inasmuch as it uses planned elements of lead time, among which are queue times, which, depending on volume and mix in the master production schedule, may or may not prevail when production actually takes place.

PLANNING VERSUS SCHEDULING

The first step in understanding the role of scheduling is to clearly distinguish it from planning. Failure to make that distinction has interfered with the appropriate application of both planning and scheduling techniques throughout the modern era of production control. For the most part, all time-phasing of order lead-time elements has been called *scheduling* by both practitioners and experts alike. The first edition of the *Industrial Engineering Handbook* (1956) considered "forward planning" to be "scheduling" [1]. One of the most influential books in the modern era, *Production and Inventory Control: Principles and Techniques*" (1967), recognized "backward scheduling" and "forward scheduling" as varieties of time-phased planning using standard elements of lead time [2]. It is not surprising that confusion carried over into the MRP era and has persisted to the present time. Early commentators on MRP thought it could do more than it could, saying, for example, "The most important feature of MRP that gave it powerful capabilities was its rescheduling feature" [3]. Real scheduling was omitted from most of the popular and influential books of the early MRP era, even though the role of scheduling and its mechanics were well defined in technical literature and in professional discourse of the time [4,5]. As a result, for more than two decades MRP was misapplied in many plants in unsuccessful attempts to schedule production.

Today the differences between planning and scheduling are well understood, even if not always correctly applied. They are contrasted in Fig. 9.8.2, which may be summarized as follows:

- A plan states what is desired, whereas a schedule states what is feasible.
- A plan may time-phase backward from a due date or forward from a start date, whereas a schedule is developed in a forward (i.e., future) mode only.
- Load projections from lead-time plans may be viewed without reference to capacity, whereas schedules are meaningful only if they are consistent with capacity.
- A plan may be made for a single order, but a schedule must consider simultaneously all orders that require the same limited production resources.

Throughout the modern era, confusion about planning and scheduling has been compounded by changes in nomenclature applied to scheduling, which may complicate a researcher's review of the literature. Classic commentators referred to *forward-scheduling* and *finite-capacity loading* [2]. Early computer simulation systems were called *simulation-mode scheduling*. As the body of knowl-

Planning	Scheduling
• Developing the *desired* sequence and duration of events for the accomplishment of production tasks	• Projecting the *feasible* sequence and duration of events for the accomplishment of production tasks
• Backward or forward	• Forward only
• Infinite capacity	• Finite capacity
• One order at a time	• All related orders simultaneously

FIGURE 9.8.2 Planning versus scheduling.

edge became more formalized by the American Production and Inventory Control Society, the preferred term for scheduling was *operation sequencing* [4,6]. When it became generally recognized that MRP and CRP, depending as they did on the assumption of infinite capacity, were feeble as a basis for scheduling, demand surged for *finite-capacity scheduling* (FCS) systems. Finally, software providers and related interests chose *advanced planning and scheduling* (APS) as the name for higher-technology systems that synchronize materials and capacity for networks of related orders, as described later in this chapter. APS is the appellation under which the prospective user will recognize professional discourse in the literature and will find state-of-the-art software (and, inevitably, some that is not state of the art) in the marketplace.

THE PROCESS OF SCHEDULING

Finite-capacity scheduling systems are available for virtually all types of production environments—job-shop, repetitive, repetitive-batch, continuous-process, process-batch, and mixed-mode. Obviously, it is important to select a system specifically suited to the manufacturing mission of the plant to be scheduled. Two major categories of systems are available: single-plant and multiple-plant scheduling. Multiplant systems are considerably more complex and are best considered as extended planning systems since they involve high-level (MPS) allocation of orders to multiple facilities.

Plant scheduling systems usually use one of four basic methods of processing orders through the plant [7]. Each method involves modeling the plant, each schedules to finite capacity, and each uses one or more prioritization rule(s). For practical purposes, each method may be thought of as a simulation of how orders would be processed through the production resources of the plant given a certain value judgment regarding the most important objective to be achieved.

Job scheduling has as its primary objective maximization of opportunity for the most important orders to be completed on time. Jobs are scheduled through all their operations in priority sequence, in effect anticipating when capacity will be needed for high-priority orders and showing what effect the arrival of those orders will have on future queuing at work centers. Job scheduling is comparatively easy to implement, easy to understand, and fast for computer processing. The theoretical concern that gaps in the schedule can cause long cycle times for some jobs seldom materializes when the system is properly used.

Resource scheduling is based on the theory of constraints, which mandates that bottleneck resources must be completely utilized. Predetermined bottlenecks are scheduled first with all operations requiring them. Then, remaining operations of each order are scheduled both backward and forward from the bottleneck. The first pass at scheduling a designated bottleneck may create overloads at noncritical work centers, requiring iterations of the backward/forward process, which consumes computer time. Consequently, resource scheduling works best in environments having few bottlenecks that do not shift between work centers.

Event scheduling uses clock-based simulation to schedule each queue at each work center on an individual basis. Time resolution is usually very fine, with the clock advancing until completion of an activity permits another activity to commence. Event scheduling usually produces good schedules, but may require long computer processing time in complex environments.

Optimization scheduling seeks to optimize a user-perceived value. Such systems have been described as "optimal seeking . . . [but] . . . do not guarantee an optimal solution." [7] Such systems are seductively dangerous, inasmuch as they appear to give the user what is asked for, no matter how wrongheaded or shortsighted the objective. For example, a schedule that optimizes short-range profit margins may have a very adverse effect on the business as a whole. Optimization scheduling requires long computer processing times under real-world conditions, so they are not always well suited for the dynamics of routine production control.

Many systems purport to be finite-capacity scheduling when in reality they are little more than computer-based manual scheduling boards. Users with serious intentions of reliable and efficient scheduling should ascertain before selection that the software under consideration employs one of the four methods described here. Within this group of four, different approaches are used by different designers, with varying degrees of elegance of simulation. The most elegant are not always the most useful, so it is important to select a system practical for operating people to use to support decisions and actions in the fast-paced, dynamic, daily routine of production control.

In this discussion, simulation-mode scheduling will be used as a framework for practical consideration of model building, priority decisions, and employment of scheduling systems in routine, direct support of production operations. There are two major types of computer simulation used in manufacturing:

- *Process design and analysis simulators,* used as needed, often in a stand-alone mode, to analyze process activities, plant layout, material flow, plant output, and product costs
- *Production control systems,* usually integrated with planning systems and used for capacity planning and production scheduling as part of the everyday execution of production plans

Process design and analysis simulation is a major tool for industrial engineers in design and problem solving, but its systems usually are not well suited for routine scheduling. Therefore, in this discussion of production scheduling, only production control systems are considered.

Simulation, of course, employs a model of the environment being simulated. The most realistic model of the plant that can be developed is set up in the computer using production resources (machines, people, tooling, etc.), future work plans for those resources (days and hours to be worked), and the productivity expected from the resources.

Processing of production orders is simulated using the model and production times for the total order backlog (usually both released and planned orders) derived from the master production schedule. To simulate realistically, two inescapable facts of life in manufacturing control must be incorporated in the simulation process:

1. Capacity of a resource, while it may be variable over time as defined in the model, is finite at any given time for any given set of working conditions.
2. Whenever the demand for capacity exceeds the finite supply, some method of prioritizing access to capacity will be employed.

These two conditions, operating together, enable the simulator to determine whether an order will obtain prompt service at a work center or whether it will wait in queue during the processing of orders of higher priorities. Thus, waiting times and operation times are simulated, enabling the manufacturing lead time of each order, and its completion time, to be determined with reasonable accuracy in advance of actual production.

Figure 9.8.3 illustrates the results of a simulation of production events in a valve plant. One of many work centers in the plant, CNCTurn is a machining center consisting of two machines operating two shifts. The scheduling system has simulated major production activities over the entire production horizon for all of the work centers in the plant. Shown in the illustration is this single work center for the first eight days of the schedule. Orders released by production control arrive from upstream work centers, wait in queue, start, and finish. Note that the queue is processed in priority sequence. In this case, relative priority is designated by an index

	CNCTurn	
Day	Machine 1*	Machine 2*
Monday August 2	**5204** (510) completes **7890** (540) starts **6646** (395) waits	**6076** (450) completes **3456** (499) starts **1234** (360) arrives
Tuesday August 3	**7890** (540) running **6646** (395) waits	**3456** (499) running **1234** (360) waits
Wednesday August 4	**7890** (540) completes **6646** (395) starts	**4567** (397) arrives **3456** (499) completes **4567** (397) starts **1234** (360) waits
Thursday August 5	**5678** (382) arrives **6646** (395) completes **5678** (382) starts	**4567** (397) running **2345** (367) released **1234** (360) waits
Friday August 6	**5678** (382) running	**4567** (397) completes **2345** (367) starts **1234** (360) waits
Monday August 9	**5678** (382) running **7519** (310) released	**2345** (367) completes **1234** (360) starts **8212** (304) arrives
Tuesday August 10	**5678** (382) completes **7519** (310) starts	**1234** (360) running **8212** (304) waits
Wednesday August 11	**7519** (310) running	**1234** (360) completes **8212** (304) starts

* *Note:* Four-digit numbers (in bold) identify production orders. Three-digit numbers (in parentheses) indicate the relative priorities of orders.

FIGURE 9.8.3 Summarized results of simulation.

number—the higher the number, the higher the priority. The next section discusses techniques of prioritization.

To produce a daily production schedule, the simulation illustrated in this example summarizes results by day; however, the actual system uses a finer time resolution, as seen in the sequence of events within each day. The actual daily production schedule corresponding to this example will be shown later in this chapter.

PRIORITY

MRP systems that use *planning dates* to drive dispatching of work in process usually prioritize by "earliest start date for the impending operation," a rule only slightly better than the alternative, "earliest order due date."

More intelligent rules are available. In fact, there is abundant literature on priority rules, with numerous sources claiming superiority for specific rules on grounds of theory or simulated results. In a context of the evolution of scheduling systems for intermittent production, Buffa and Miller provide a comprehensive summary of the formative period of priority research from 1955 to 1979 [8]. Figure 9.8.4 is representative of the conclusions of this research [9].

While many theoretical arguments about priority can be dismissed as impractical, the conclusion is inescapable that the best basis of prioritization is some variant of slack time. *Slack time* is, of course, the difference between demand time and supply time. With respect to a pro-

	Performance of priority rules					
	Minimum processing time	Minimum average slack	First come, first served	Earliest start date for impending operation	Earliest due date of order	Random
Quantity of orders completed	Best	Good	Good	Good	Excellent	Good
Percent late orders	Good	Best	Poor	Poor	Poor	Poor
Completions early	Best	Fair	Poor	Poor	Fair	Good
Target accuracy	Poor	Best	Poor	Poor	Poor	Poor
Quantity of orders in queue	Best	Fair	Fair	Fair	Good	Fair
Average wait time	Best	Fair	Poor	Poor	Fair	Fair
Carrying cost of work in process	Good	Excellent	Good	Excellent	Best	Good
Ratio of inventory cost while waiting to that while working	Equal	Equal	Equal	Equal	Equal	Equal
Labor utilization	Best	Excellent	Excellent	Excellent	Good	Excellent
Machine utilization	Best	Excellent	Excellent	Excellent	Good	Excellent
Weighted composite		Best				

FIGURE 9.8.4 Performance of priority rules.

duction order, it is the difference between the amount of time remaining before the required date and the amount of lead time yet to be executed on the order. Among competing orders, the one with the least amount of slack time should be processed first. An advantage of a slack time rule is that it is dynamic, meaning that unless a day's worth of work is done on an order each day, slack will decrease and the priority will increase. A classic example of a slack time rule is *critical ratio,* in which an index number, calculated as the ratio of demand time to supply time, designates the priority [10].

Figure 9.8.5 depicts the elements of planned lead time for a production order, the current status of which is shown at the arrival of the order into the queue of work center 2. Information needed to calculate critical ratio is as follows:

B = beginning date
C = critical ratio
D = date due
E = ending date
H = hours worked per day
L = lead time remaining in days
M = standard move time in days
N = lot size
P = productivity
Q = standard queue allowance in days
R = unit run time in hours per piece
S = setup time in hours
t = delivery time remaining
T = today

Using the relative date convention shown in Fig. 9.8.5, the critical ratio of the order at that time can be calculated. As can be seen in the figure, this point in production was planned for the end of day 513. The amount of planned lead time remaining is from 514 through 525 inclusive, or 12 days. Actual delivery time remaining is from today, 517, through 525 inclusive, or 9 days. The calculations to arrive at these values are as follows:

$$L = E - B + 1$$

$$= 525 - 514 + 1 = 12$$

		Part No. Main Shaft		Job No. 123		Quantity 60	Lead Time 4 weeks	
Queue Time	Start Date	Opr. No.	Work Center	Setup	Run	Job Time	Finish Date	Transit Time
0	506	1	4	0.2	.05	3.2	506	0
1	508	2	1	0.5	.25	15.5	509	1
0	511	3	6	–	–	–	512	1
1	515	4	2	1.0	.15	10.0	515	1
1	518	5	3	1.0	.20	13.0	519	1
1	522	6	5	0.7	.30	18.7	523	1
0	525	Stock						

$T = 517$*

*Dates are relative manufacturing days for ease of calculation.

FIGURE 9.8.5 Planned lead time.

$$t = D - T + 1$$

$$= 525 - 517 + 1 = 9$$

If the days of planned time were not already known from Fig. 9.8.5, lead time remaining could be calculated in detail as follows:

$$L = \sum (Q + M) + \sum \frac{S + NR}{HP}$$

A detailed treatment of this planned lead time calculation is given in Ref. 11. Critical ratio is, then, as follows:

$$C = \frac{t}{L}$$

$$= \frac{9}{12} = 0.75$$

This order has negative slack because actual time to the required date is less than the amount of planned lead time to complete the order. Slack is 9 days of time remaining minus 12 days of lead time remaining, or –3 days. The ratio is 0.75, which, since it is less than unity, indicates the order must be expedited. If the ratio had been greater than unity, it would have indicated that the order had some slack time.

Critical ratio expresses the percentage of the remaining planned manufacturing lead time that actually exists between now and an order's due date. It is an index of the relative priorities among a group of orders. The critical ratio priority rule is to run orders in ascending sequence of slack. A critical ratio may be positive or negative. The more positive a critical ratio is, the lower the priority; the more negative a critical ratio is, the higher the priority.

An expanded version of critical ratio, considering the rate at which inventory is being depleted compared to the rate of depletion of manufacturing lead time, is available for make-to-stock environments [12].

The prioritization rule employed in a simulator must, of course, be the one that will be used on the production floor. In actual practice, few plants use the rules favored in the literature. In fact, lack of discipline in prioritization is a major weakness of many production control operations. Practitioners desiring to follow a rational rule for scheduling should examine the literature before accepting the offering of software under consideration.

REFINING THE MODEL

Production facilities vary greatly in their complexity of process flow and their characteristics of production activities. It is therefore useful—even essential—for the scheduling system to have enough flexibility to support sufficient accuracy of process modeling. It is inevitable, however, that trying to refine excessively a production model requires excessive amounts of time and effort to set up and maintain the model and to interpret and use system outputs. It is necessary to be practical in the degree of exactitude that is sought. After all, unforeseeable events will to some degree introduce dislocations into the schedule to which regular rescheduling will need to react. Any good schedule is a *reasonable prediction* of future events, not an absolute certainty. The practical user will avoid systems that excessively refine the model at the cost of laborious maintenance of the system.

Some system refinements are so basic as to be essential for reasonable accuracy. The ability to handle operation overlapping and outside processing operations are examples of basic variations. Other, more advanced functions may be highly desirable for some users.

The ability to schedule multiple constraints simultaneously may be necessary to get a viable schedule. For example, work center A consisting of four machines and work center B consisting of three machines may both be served by a pool of five machine operators. A usable schedule can be obtained only if the system can recognize the simultaneous availability of a machine and an operator.

In many production environments, group technology scheduling is a highly desirable capability. *Group technology* is a technique for identifying and bringing together related or similar components in order to take advantage of their similarities in the design and manufacturing process. Grouping like items together in the production schedule can contribute significantly to productivity by permitting multiple orders to be produced from the same setup or from minor changes in setup. A code identifying similar characteristics may be extracted from an item's group technology code, where such is available, or some other code for setup group, tool number, dimension, temperature, color, or other shared attribute. The scheduling system can group or suggest grouping orders based on similarity, or it can sequence such orders where a progression in some attribute—say, color—is desired.

Processing orders in a sequence different from that dictated by priority may cause deviation from the needs of the master production schedule if the MPS is not constructed consistent with group technology. Since group technology scheduling involves a trade-off between commitment dates and plant productivity, the scheduling system should incorporate decision rules enabling the user to specify limits of schedule rearrangement.

Chapter 17.6 of this book provides a general treatment of group technology.

USES OF SCHEDULING

A major part of the industrial engineer's mission is to simplify the production environment to the maximum extent feasible. Some environments, however, are inherently complex and remain so even after utilization of appropriate process technology and application of exemplary engineering practices.

The more complex the environment, the more difficult it is to schedule. Characteristics contributing to scheduling difficulty are product variety, process difficulty, product structure complexity, and susceptibility to schedule changes [13]. While uses of scheduling are substantially the same in all discrete manufacturing applications, the value of simulation-based systems rises with the degree of complexity.

A key use of a scheduling system is to derive a reliable expectation of when production orders will be completed. A well-designed system in a reasonably disciplined environment provides *advance visibility* of production outcomes, which enables proactive management actions to be taken to change undesirable outcomes. Every operating manager can say, "Show me the future and I will manage better today." Indeed, in a production environment of any significant complexity, no planning tools can approach the effectiveness of computer simulation as a basis for decisions, actions, and predictions of completion times.

The objective of reliable completion time prediction for products with structured bills of materials imposes a major requirement on the scheduling system. It must be capable of *network scheduling*—that is, it must be able to recognize and appropriately schedule dependency relationships defined by the bill of materials. Components must be scheduled when materials will be available, subassemblies when components will be complete, and assemblies when they will have subassemblies. A suitable system to schedule structured products will simulate production orders in their dependent relationships, identifying the source of supply and availability time for each constituent, whether manufactured or purchased. Availability of a simulation of this scope early in the life of an order for a complex product is a highly productive diagnostic aide and an essential tool for schedule compliance. Uses of network scheduling are cited in the case study later in this chapter and in Ref. 13.

Since a valid schedule is consistent with the finite capacity of production resources, scheduling is inseparable from capacity planning and control. A major use of the scheduling process is the control of capacity to execute the production plan. Load profiles generated by capacity requirements planning assume that queuing at *all* work centers for *every* order will *always* be what was *planned.* Since the dynamics of the real world invalidate these assumptions continually in most plants, CRP is useful only for planning average levels of resources required. It has been shown that efforts to use CRP for short-term capacity planning will inevitably fail in even moderately complex environments [6,11].

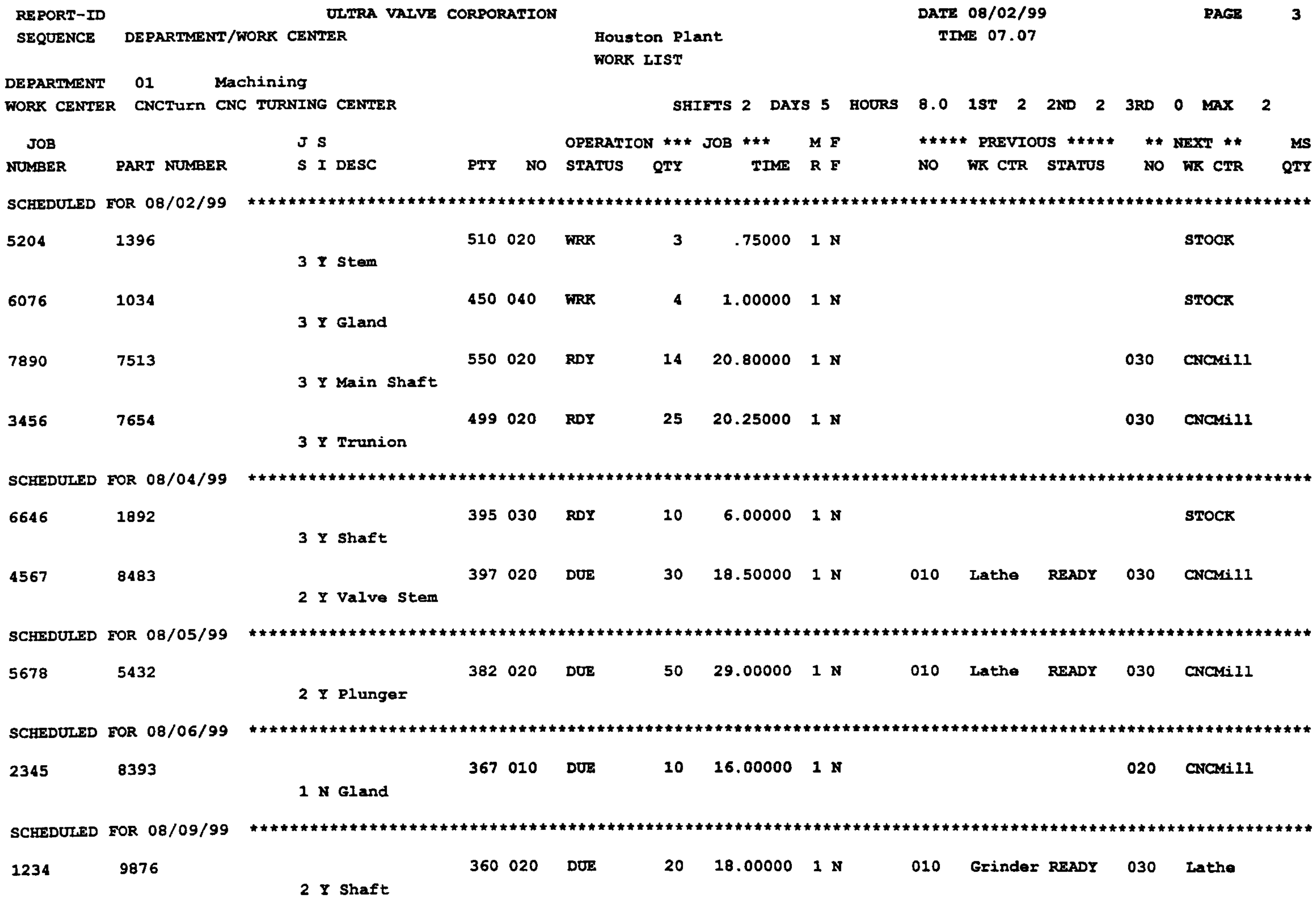
Simulation of workloads that can be expected at work centers in future periods is the best basis for realistic capacity decisions. Here concentration is not primarily on the *workloads* themselves, but rather on the production *delays* that will be caused by constraints. This is consistent with the dominant drivers of contemporary manufacturing: *time* and production *flow.* Simulation shows where and when delays will occur unless capacity is adjusted. It shows where and when idleness will occur due to upstream constraints. It becomes, therefore, the preferred basis for decisions and actions to control capacity.

The essence of a schedule is, of course, the sequence in which operations on orders must be processed. A major use of scheduling is to communicate to each production resource what must be produced and in what sequence. Thus, priorities planned in the master production schedule are translated into execution instructions for the plant in the form of dispatch or work lists. A representative work list for the plant described in Fig. 9.8.3 is shown in Fig. 9.8.6. Production orders on the work list correspond to the simulation of events summarized in Figure 9.8.3.

In a make-to-order environment, the scheduling system is the vital source of information for customer order servicing. Throughout the life of a customer order, the predictive capability of simulation monitors order progress and conformity to commitment. For a structured product, network scheduling links the sales order to the source of supply for every constituent, so that any potential lateness is immediately identified with its cause and degree of influence while there is still time for corrective action.

MAKING IT WORK

One of the most limiting performance problems for many manufacturing plants is the gap between plans for production and actual execution of those plans. A plant determined to



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REPORT-ID                     ULTRA VALVE CORPORATION                            DATE 08/02/99            PAGE    3
SEQUENCE    DEPARTMENT/WORK CENTER                      Houston Plant              TIME 07.07
                                                        WORK LIST
DEPARTMENT   01      Machining
WORK CENTER  CNCTurn CNC TURNING CENTER                            SHIFTS 2  DAYS 5  HOURS  8.0  1ST  2  2ND  2  3RD  0  MAX  2

  JOB                         J S                       OPERATION *** JOB ***    M F       ***** PREVIOUS *****    ** NEXT **     MS
NUMBER      PART NUMBER       S I DESC         PTY   NO STATUS    QTY       TIME  R F       NO    WK CTR   STATUS    NO  WK CTR    QTY

SCHEDULED FOR 08/02/99  **************************************************************************************************

5204        1396                               510 020  WRK         3     .75000  1 N                                   STOCK
                              3 Y Stem

6076        1034                               450 040  WRK         4    1.00000  1 N                                   STOCK
                              3 Y Gland

7890        7513                               550 020  RDY        14   20.80000  1 N                              030  CNCMill
                              3 Y Main Shaft

3456        7654                               499 020  RDY        25   20.25000  1 N                              030  CNCMill
                              3 Y Trunion

SCHEDULED FOR 08/04/99  **************************************************************************************************

6646        1892                               395 030  RDY        10    6.00000  1 N                                   STOCK
                              3 Y Shaft

4567        8483                               397 020  DUE        30   18.50000  1 N      010   Lathe    READY    030  CNCMill
                              2 Y Valve Stem

SCHEDULED FOR 08/05/99  **************************************************************************************************

5678        5432                               382 020  DUE        50   29.00000  1 N      010   Lathe    READY    030  CNCMill
                              2 Y Plunger

SCHEDULED FOR 08/06/99  **************************************************************************************************

2345        8393                               367 010  DUE        10   16.00000  1 N                              020  CNCMill
                              1 N Gland

SCHEDULED FOR 08/09/99  **************************************************************************************************

1234        9876                               360 020  DUE        20   18.00000  1 N      010   Grinder  READY    030  Lathe
                              2 Y Shaft
```

FIGURE 9.8.6 Daily production schedule. *(Courtesy of Manufacturing Management Systems, Inc.)*

overcome this limitation, and thereby to secure superiority in manufacturing, will develop a state-of-the-art production scheduling capability. This development involves improved practices as well as appropriate capital investment.

If a new system is to be implemented to support the scheduling function, it should be implemented in accordance with proven principles of system implementation, which are thoroughly explained in the literature [14]. If the system is a simulation-mode scheduler, its use must follow two fundamental principles of simulation. The first of these is as follows:

Describe to the simulator, with reasonable accuracy, how the process will work.

Process description begins with routings. They must completely describe the process, including all steps of production that contribute to lead time. If temporary conditions require a deviation from the standard routing, that deviation must be incorporated in the affected production order.

Production standards or estimated times should be reasonably accurate. On the average, productivity factors used to estimate capacity will correct for any consistent bias in the standards, but individual order delivery estimates depend on reasonable accuracy of estimated production times.

Productivity data (i.e., utilization and efficiency) should reflect demonstrated performance, not a theoretical allowance or a desired goal.

The plant model is based on the number of people, machines, or other production resources that are to be employed by time period. Realism in plans for these resources is essential for reliable modeling.

The second simulation fundamental is as follows:

Behave in reasonable conformity to what you told the simulator you would do.

Decision rules built into the system must be followed. For example, rules of prioritization will control estimated completion times developed by the simulator. Production supervision must, therefore, comply with generated production schedules in order for the simulation to be a reliable imitation of what to expect for customer service.

As plans are executed, the magnitude of the total workload and the lead time remaining for each order must be portrayed to the next simulation by accurate production status reporting. While data collection is easy with contemporary technology, a surprising number of plants do not report status with the timeliness and accuracy required for dependable simulation.

The objective of advance visibility is better proactive management, and the mission of the production control function is to manage the lead time of the product. This mandates aggressive load management, using the output of simulation to support decisions and actions as the dynamics of customer demand and production events continually change the picture portrayed by the simulator. Experience has clearly shown that users of a scheduling system must know not only how to operate the system, but, through formal policies and procedures, how to run the business with the system [14].

INTEGRATION

A scheduling system may be used as a stand-alone execution application or it may be used as the execution phase of an integrated system of manufacturing planning and control. When it is desirable to join the execution system from one vendor to planning applications from another vendor, that integration is relatively simple [7,15].

The most common mode of integration with an existing database is to transfer ASCII text data to the scheduling system. This involves relatively easy programming to read the database, extract the prescribed data elements, and format the data in a manner specified by the scheduling package. At a minimum, required data includes status of production orders and capabilities of production resources. More powerful systems will also use supply and demand information and other scheduling parameters. If the scheduling system is processed on the computer containing the planning database, the scheduler acquires the needed information each time scheduling is processed. If the planning database is on a computer being used as a data warehouse, the interface files may be passed to a server (a PC or workstation) located in the production control office or some other convenient location.

An interface between the planning database and the scheduling application may be made using open database connectivity (ODBC) technology in environments where ODBC compatibility exists.

If the scheduling software is self-contained (i.e., has complete displays and reports from the scheduling process), it is usually not necessary to transfer data back to the planning database. Otherwise, programs similar to the transfer-in programs are used to transfer out.

SCHEDULING AND COMPETITIVE PERFORMANCE

Earlier in this chapter, scheduling was described as "the centerpiece of the production execution infrastructure." It has that importance because excelling at schedule management actualizes a crucial set of competitive advantages. Most important of these is increased *production velocity.* The ratio of value-added time to total lead time increases as lead times are shortened by the elimination of delays at potential constraints. Advance visibility is the key to proactive load management and *short lead times.*

Shorter lead times create *reduced work in process.* Less working capital is bound up in stagnant backlogs on the shop floor. Perhaps more than any other reason, the quest for *on-time deliveries* energizes the initiative for better scheduling. With regular simulations of future outcomes, the effects of changing conditions can be seen and immediate actions can be taken to correct or avoid delivery-threatening problems. Valuable in any environment, this capability is vital in make-to-order plants.

Schedule compliance is accompanied by other improvements in *responsiveness to customers.* Reliable knowledge of future production conditions supports confident responses to customer delivery requests.

The superiority of simulation over CRP for projecting future workloads facilitates optimum utilization of people and production equipment, thereby *increasing productivity.* In plants having significant opportunities for group technology scheduling, reductions in setup time further increase productivity of direct resources. Support resources—production control, master scheduling, and customer order servicing personnel—are dramatically more productive when the computer does the detail work of scheduling orders, illuminating problems, clarifying facts, and eliminating expediting.

A collateral benefit of schedule discipline is *improved communications* throughout the organization, resulting from reliable, factual information being made available to people in manufacturing, sales, and management.

The result of all these improvements is *increased profits.* Short lead times, service to customers, low inventory, and plant productivity are the consistent characteristics of excellence in execution, a sure way to formidable competitive advantage.

CASE STUDY

Background

Danuser Machine Company is an interesting case study in production scheduling for two reasons: (1) It is a small manufacturer with typical scheduling needs, and (2) at the beginning it encountered and overcame common problems in its selection and implementation of scheduling software. So instead of featuring a large company with a large budget and sophisticated information technology (IT) resources, this case study examines a small company with a limited budget and competent, but not extensive, IT resources. The Danuser experience demonstrates that state-of-the-art systems are available, affordable, and manageable by companies of all sizes. It also provides the kind of tutorial useful to any company setting out to improve scheduling systems and practices.

Danuser manufactures a variety of products for urban and farm use. Among these products are posthole diggers, post drivers, and OEM components. Sales are to distributors and original equipment manufacturers. Some items are produced to order, and others are made to stock.

The plant employs about 77 people engaged in fabrication, machining, and assembly. Some operations are performed by outside processors.

Danuser has used manufacturing and accounting systems processed on a midrange computer since 1979. MRP has been successfully used for material planning since 1983. A data collection system provides timely status of production orders in the work-in-process system. Capacity requirements planning (CRP) (i.e., backward planning to infinite capacity) associated with the MRP system proved to be so limited in useful information compared to maintenance effort that it was not regularly used.* In summary, Danuser had what many plants have—production planning and WIP tracking. And it also lacked what many companies lack—capacity planning and production scheduling. Danuser filled the systems void in the way similarly situated companies do—that is, an employee with long shop experience manually scheduled orders and expedited them as changing conditions (day by day and hour by hour) required.

Eventually, evolution of business circumstances exerted strong pressure for change. The business began to grow, reaching a 20 percent average annual growth rate for two consecutive years. Increasing capacity by adding another shift proved impossible due to the shortage of labor in the immediate area.

Therefore, maximizing effective throughput by means of advance planning of capacity and strict prioritization of scheduling became critical. To complicate the situation, longtime employees began to retire, including the key production scheduler, who was replaced with an able but much less experienced person. Delivery promises were missed; the effect of new orders could not be anticipated accurately; and the impact of daily dislocations—operator absences, machine downtime, quality problems—could not be assessed for corrective action. It became clear that access to more complete, yet at the same time more selective information was needed—a job for information technology.

But what kind?

For a period of eight years the company had had a sustained interest in and curiosity about finite-capacity scheduling (FCS). It was thought that the high cost of good software packages placed them out of reach of a small company. However, continued tracking of the trend toward PC-based systems using reasonably priced, but fully capable software led to a thorough investigation of available FCS software.

A Bad Start

At this point, Danuser experienced a realization of inadequacy that is common to many who start shopping for scheduling software: company representatives did not know enough about the subject to evaluate confidently their needs and the claims of software vendors. What they thought they knew had been gleaned from articles, advertisements, sales brochures, and a few marketing presentations. But the further they proceeded, the more unanswered questions they had and the more confusing the terminology and claims of vendors became. The number and diversity of FCS packages on the market was almost overwhelming. Then, at a trade show, they encountered a well-advertised software vendor with an irresistible offer: take the software free of charge and try it out for a period of time before making a decision of whether to pay for it. Danuser accepted the offer.

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* See under Uses of Scheduling heading in this chapter for a discussion concerning the limitations of CRP.

It turned out that "free of charge" was not the same as free of effort or free of investment of time by key personnel. The vendor provided—and the customer paid for—a short period of so-called guidance by an application consultant. To Danuser's dismay, this person, while intelligent and conscientious, knew virtually nothing about manufacturing and had no experience in implementing the system. Without experienced guidance, the system analyst at Danuser programmed the interface between the application and the planning database.* Left on their own after the initial consultation, unable even to get reliable advice by telephone, Danuser people experienced several months of wasted time and mounting frustration trying to adapt the software to their production environment. The design of the system was complicated, so it was not intuitively obvious how it should be applied. Finally, without ever succeeding in producing a satisfactory schedule, Danuser gave up on what may in fact have been an adequate, but complicated, system.

Doing It Right

Danuser's need for better control of production execution persisted, so members of the project team persevered. They had looked at another software package prior to being distracted by the "free trial" offer. They took another look, including talking to two manufacturing plants experienced in using the software under consideration. The software was more understandable than the package they had first tried, and it appeared very practical for everyday use by production people. From the vendor they were assured of implementation counseling and training from a consultant with solid manufacturing experience, one with whom everyone at Danuser felt confidence. So they started again.

The database created by planning applications—sales orders, MRP, work-in-process, inventory, purchasing—resides on the existing midrange computer. This data is passed to a PC in the production control office for scheduling. Programming the interface to the database went smoothly using a set of templates furnished by the vendor. Judged somewhat easier than their first experience, programming took less than 40 hours for the complete application, including network scheduling.†

Danuser realized that its practices for sending out orders for outside processing was unique, so a minor customization of the software was needed to facilitate accurate process modeling. The vendor incorporated this customization before delivery of the package.

Reengineering Production Support

To implement the system, Danuser followed the structured methodology recommended by the vendor, which not only addressed technical tasks, but also emphasized how the system would be used to operate the business.‡

As is so often the case, Danuser discovered that an FCS implementation is the ideal opportunity to reengineer existing practices in production control as well as activities in other departments in support of manufacturing. An important implementation task was development of an operations manual for production control, one that would contain policies and procedures for carrying out regular business activities with the system.

For example, a key policy issue is how sales orders are to be promised and prioritized to properly support the prioritization of production orders for scheduling.§ Concurrence of top management was obtained for this issue, which had never been formally clarified before. Routine production control procedures were developed and documented, such as how outside service operations are to be handled and how production orders are to be put on hold or delayed scheduling, if required. It was determined that existing practices of order planning and release could be reengineered for greater effectiveness, so new procedures were documented. The result was a simple, straightforward manual of improved policies and procedures, which was genuinely needed by an organization that had operated informally and sometimes inconsistently in years past.

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* See under Integration heading in this chapter for an explanation of the interface process.

† See under Uses of Scheduling heading in this chapter for an explanation of network scheduling.

‡ See Ref. 14 of this chapter for a methodology of system implementation.

§ See under Priority heading in this chapter for a discussion of priorities for scheduling.

Start-Up

As is usually the case, reengineering and documentation of improved production support processes took more time than start-up of the computer system. Both aspects of implementation were supported by the consultant, who also conducted thorough training for production control personnel and production supervisors. An appropriate level of training was provided for top management and important nonusers. The total elapsed time for implementation—interface programming, customization, reengineering, training, and pilot operation—was 10 weeks from delivery of the software to production cutover, with the critical path being reengineering to enable people to exploit the new resource of abundant information. Benefiting from short, but thorough, pilot operation, production cutover proceeded smoothly.

The scheduling process proved to be fast on the production control computer (Pentium II®, 266 MHz). A data consolidation taking about 6 minutes occurs at the beginning of each workday. Thereafter, about 3000 production orders can be scheduled (or, as is often desired, rescheduled) over 54 work centers in 3 minutes, including group technology and network scheduling.

Emphasis on Execution

Start-up for the users also went smoothly. Production supervisors were accustomed to receiving a dispatch list from the work-in-process system. This was replaced by the prioritized work list from the new system. For production control personnel, major new capabilities are available. Profiles of load and capacity inform participants about the overtime decisions made each week and also support other load management actions (e.g., redistribution of load and staffing). The ability to finitely schedule multiple constraints is especially helpful in dealing with shortages of qualified operators. And, of course, the ability to schedule dependency relationships shows the anticipated effects of both material deliveries and capacity constraints on sales order deliveries.

Concentration on production execution, especially the primacy of *time* as a driver of manufacturing, has increased the sensitivity of production people to details of production support, leading to additional refinements in the timing of production order release, suitability of lot sizes, maintenance of order integrity, and timeliness of material availability. For Danuser, development of better production scheduling involves a broader mandate: to improve performance in all aspects of production planning and execution.

Lessons of Experience

Is Danuser an instructive case study in production scheduling? Which aspects of the company's experience can be considered common and which unique?

The initial motivation for studying FCS is common: determination to improve performance in production execution. The need for a complete, integrated planning and execution system is recognized as fundamental to manufacturing excellence. Other companies pursuing this objective will, like Danuser, find an abundance of FCS software available, and they might also decide to add to their planning applications a scheduling package from a different vendor.

It should be rare for a company to acquire a totally unsuitable package as Danuser initially did. However, the plethora of software products, their design differences, arcane terminology, and extravagant claims are, without doubt, hazards for the uninformed. Above all, the design of the chosen software must be congruent with the manufacturing mission of the plant. A company needs to know the basics of contemporary technology before shopping for software. This chapter is a good place to start if education is needed. Conferring with experienced users will be valuable, but, as Danuser found out, guidance by a consultant or other leader with *practical production experience* may be the difference between success and failure.

With the right base of knowledge, selecting a practical package, and following a sound methodology of implementation, start-up of production scheduling should proceed smoothly and promptly, as it did with Danuser after it combined these three essentials for a second start. Danuser, like any successful user, concentrated not only on a better system, but also on how to run the business better with that new system.

CONTINUING EVOLUTION

Evolution of production scheduling in the modern era has been driven by the synergy of computer power and application design. An abatement of that dynamic is not likely. Therefore, the expectation for more powerful scheduling systems is linked to the expectation of continuity in trends for computer technology, key characteristics of which are increased computational power, lowered costs for that power, greater efficiency of network connectivity, and enhanced naturalness of the human interface.

As to the design of future systems, continued dominance of simulation-mode scheduling may be expected, certainly insofar as practicality is concerned. While quantitative methods have historically occupied a major place in the curriculum of industrial engineering, their success in industry has not been proportionate to their academic favor.

Current trends in APS systems will likely continue to dominate the evolution of systems design. Chief among the essential characteristics for future designs is simultaneous planning of materials and scheduling of capacity. The process must be fast so that operations may be scheduled on demand in both *production* and *what-if* modes. Scheduling will be synchronous with real-world, real-time events, such as receipt of an inquiry or entry of a customer order, but will be consistent with the need for a degree of stability in short-term execution activities. Finally, systems must be made more practical for everyday use by operating people. A priority should be to reverse the contemporary trend toward creating sophisticated, elegant, and technically impressive software that is baffling, burdensome, and ultimately alienating to the people who have to use it.

Improvements in systems must be accompanied by improvements in the general level of execution disciplines on the part of production support and operating personnel—and of management as well. Systems exist today with functionalities surpassing the abilities of many manufacturing organizations to use or benefit from them. State-of-the-art production scheduling systems demand operating people determined to execute the schedule on time, every time.

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BIOGRAPHY

Ray Lankford is president of Manufacturing Management Systems, Inc., a firm providing production scheduling software to the manufacturing industry. For 10 years he was associated with George Plossl in counseling and education in the field of production operations management. His career in manufacturing management includes production operations, manufacturing engineering, industrial engineering, and materials management. As vice president of operations for McEvoy Oilfield Equipment Company, Lankford was responsible for four plants around the world. Prior to that, he was vice president of manufacturing for the Reed Tool Company. He is a registered Professional Engineer, certified as a Fellow by the American Production and Inventory Control Society. Lankford has served as chairman of the APICS Certification Committee on Capacity Management. A contributor to the *Production and Inventory Control Handbook,* he has written numerous articles on capacity planning, production scheduling, and production activity control.

CHAPTER 9.9

CASE STUDY: AN EFFECTIVE PRODUCTION SYSTEM FOR THE AUTOMOTIVE INDUSTRY

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Ingersoll, Ontario, Canada

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This chapter will discuss the Suzuki Production System at CAMI Automotive Inc. It will provide insight into the fundamental redesign of the organization's operating philosophies and the working environment that achieved dramatic improvement in the areas of safety, quality, productivity, and cost. By understanding and implementing the fundamental elements of the system and focusing all support activity on the shop floor operator, systemic changes occurred that empowered all CAMI team members (hourly and salaried). The entire organization now works toward common goals and objectives, and one vision.

This chapter focuses on how this production system works to drive the organization to global competitiveness and to become a world-class manufacturer.

BACKGROUND

CAMI Automotive Inc., is a joint venture between General Motors and Suzuki Motor Company. CAMI manufactures entry level automobiles for the global market. Prior to the start of production, Suzuki introduced the Suzuki Production System to the new CAMI workforce. By the start of production in 1989, the Suzuki Production System began to deteriorate. The systems used at Suzuki are the same systems that drive everyday life in Japan. At CAMI, it wasn't understood that training would be required in why the maintenance of the system was important. The importance of the system was not evident, and it deteriorated further. The result was that CAMI came very close to being a traditional North American automotive plant, with few of the original benefits in place.

In 1994, the organization recognized that it needed to go back to basics and reintroduce the Suzuki Production System with a North American twist. In 1995, the Suzuki Production System Department was formed. The objectives of the department were to expose CAMI team members to the benefits of the system and to create an environment in which all team members live and breathe the Suzuki Production System.

THE SUZUKI PRODUCTION SYSTEM

A production system is a system of concepts, philosophies, and rules to run a business. The Suzuki Production System (SPS) is a set of basic operating philosophies that support team members in the manufacture of vehicles, with the foundation being standardized work. It is a derivative of the Toyota Production System, and is characterized by systems that are constantly evolving and improving from a baseline.

Figure 9.9.1 is a graphic depiction of SPS. Each one of these pillars supports the system, and neglecting any one of them will compromise the entire system. "Cherry picking" elements to implement based on ease of implementation or personal preference contributed to the initial deterioration of the system at CAMI, and there was a determination not to allow that to be repeated. Recognizing this, a number of steps have been taken:

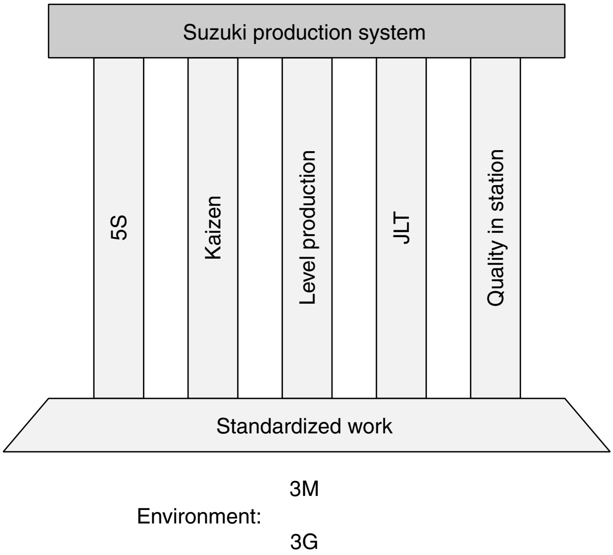


FIGURE 9.9.1 The Suzuki Production System pillars.

- The SPS Department was established.
- Additional resources were dedicated, including pilot teams and task forces.
- The executive team now takes an active role in supporting SPS efforts, including time commitments for weekly report-outs, and departmental initiative tours.
- Training has been established for the entire organization.

Benefits of the Suzuki Production System

- Focuses all support on team members to ensure a safe working environment and a high-quality, low-cost product.
- Drives down the per-unit cost by continually identifying and eliminating waste.
- Builds in a high degree of flexibility that allows quick reaction to changes in the market or product. This offers a competitive edge in the global marketplace.

- Empowers individuals to be deeply involved in all aspects of their workplace. This enhances their skill levels, builds pride, ensures continuous improvement and reduces the need for technical experts (e.g., engineers).
- A strong system, followed consistently by all team members, reduces the need to be reactive, and moves the company beyond the fire-fighting mode. Attention then shifts to cause analysis and the permanent solution to problems. Real growth and improvement cannot occur in a reactive environment.
- All methods and procedures are standardized. This minimizes deviation, yields standard quality, and makes problem solving and accountability a reflex.
- The system gives us a blueprint to follow rather than the particular management style of an individual.

The Elements of the Suzuki Production System

Standardized Work. Standardized work is the foundation for the Suzuki Production System pillars, and if it is not firmly in place, the effects of all other elements are weakened. All processes are broken down into small work elements, sequenced to ensure safety, quality, and efficiency. All team members from both shifts rotate into each station and are expected to follow the standard for that workstation.

Benefits of Standardized Work:

- Improved safety
- Consistent quality at a high level
- Training consistency and effectiveness
- Recognizable baseline for kaizen and problem solving
- Supported quality systems
- Reduced production costs, and increased profits and job security

5S Development. The following elements compose the 5S system, which brings order and cleanliness to the workplace.

- Simplify

  Distinguish between necessary and unnecessary items.

  Eliminate unnecessary items.
- Systemize

  Increase job efficiency by creating a well-ordered workplace (a place for everything and everything in its place).

  Provide easy access storage/filing system.

  Label for easy identification.
- Sanitize

  Eliminate dirt and dust to make the workplace clean and safe.
- Standardize

  Thoroughly implement the first three items by standardizing work methods and activities.
- Support

  Ensure all team members are trained and correctly maintain systems in team areas.

  Lead by example.

Benefits of a Strong 5S System:

- A safe work environment
- Improved morale and pride
- Improved machine uptime
- An efficient workplace
- Strong visual controls to improve quality (e.g., parts labeled, tools properly stored)
- Reduced cost of production by improved waste identification

Kaizen. Kaizen (continuous improvement) begins with identifying problems and waste in the workplace. Potential solutions are proposed, tested on-line, and then implemented. Kaizen must be a daily event and is more effective if generated and implemented by the team members to ensure success. They are the experts within our system. They know the jobs. They know the problems, and in most cases, they know the solutions. The Suzuki Production System creates the environment that encourages and supports this activity.

Level Production. In the overall leveling of options and volume, fluctuations can generate waste both in machinery and staffing. For level production to be effectively achieved

- Volumes must be averaged and kept at a constant level (hourly, daily, weekly, and monthly).
- The model mix (e.g., 2-door versus 4-door model) needs to be averaged through the process to minimize the effect on the team member to avoid overburdened or underutilized conditions.

Benefits of Level Production Include:

- The system is as efficient and flexible as possible without overburdening employees.
- Production is balanced among all processes.
- Just-in-time production is possible.
- Standardized work is sustainable.
- Quality and safety are not compromised.
- An enhanced relationship with suppliers is encouraged.
- Reduced cost of production is possible.

Managing a level production schedule requires an acknowledgment that off-standard conditions will occur at times. It is imperative that a plan of action is implemented to deal with those situations that will affect level production.

Just-in-Time. A just-in-time system allows for the manufacture and delivery of only what is needed, when it is needed, and in the quantity needed. It attempts to manufacture with the absolute minimum of in-process inventory, resulting in shortened lead time and tremendous savings in carrying costs.

Benefits of Just-In-Time:

- Provides a steady supply of parts.
- Prevents excess inventory and limits in-process stock.
- Allows for kaizen of packaging, delivery, and racking.
- Offers inventory accuracy (fewer impacts on production uptime).
- Provides quicker identification, problem solving, and resolution of defective parts.
- Supports standardized work.
- Reduces cost of production.

Quality in Station. This pillar of the Suzuki Production System simply means that defects will not be passed on to the next operation or customer. There are several elements that ensure that quality is built in at the station.

Autonomation—Passive devices (e.g., limit switches) are built into machines that not only alert the operator that a problem exists but also shut down the operation. This prevents defective parts and eliminates the need to have an operator at the machine.

Andon system—If a team member discovers an error or is unable to complete the process, a signal is sent to the andon board, which alerts the team leader. The problem can then be resolved before the vehicle leaves the station. Repairs can be done more effectively and efficiently at the workstation than off-line.

Error-proofing—Team members maintain parts label codes, implement color codes, and rider (manifest) sheet information to ensure the correct parts are installed. Racks of sequenced parts often rotate in one direction to ensure correct part selection.

Self-checks—Team members do a 30-second visual check of their process every 2 hours. In addition, a total of 15 minutes per vehicle is spent hand checking all critical fasteners with click wrenches followed by a paint marker signifying that the torque and check have been completed. This is done by the operator at the station where the critical fastener is installed.

Design for manufacturing/assembly (DFM/A)—Team members are active in the DFMA program. Many ideas for design are generated to ensure a quality build. A total manufacturing cost model was developed to incorporate nontraditional elements (e.g., frustration, morale, line balance flexibility) to better support the operator.

Support Mechanism Within the Suzuki Production System

The six elements of the Suzuki Production System in themselves ensure nothing. It is the environment created and sustained in the workplace that makes the production system work. CAMI's values of team spirit, kaizen, empowerment, and open communication drive the system.

Team leaders play a pivotal role in the success of the Suzuki Production System. They are instrumental in the implementation of all elements of the system, facilitate and focus team projects, and audit the effectiveness of the system. Their 1:6 ratio to their teammates ensures that support is immediate to maintain the quality of the team's environment and its product.

Pilot teams play another key role within our system. Team members come off the floor for a two- to three-year assignment. Their role is to support production teams by maintaining standard work, visual management, and to assist the team in problem-solving projects and line balancing activities. These teams are at the center of all activities during new model development and launch.

A critical point in launching a Japanese-based production system is ensuring that the team members have access to a kaizen shop. This allows quick implementation of team-generated improvement ideas. A large part of the supportive environment is empowerment. Nothing frustrates the individual more than the promise of empowerment with nothing backing it up.

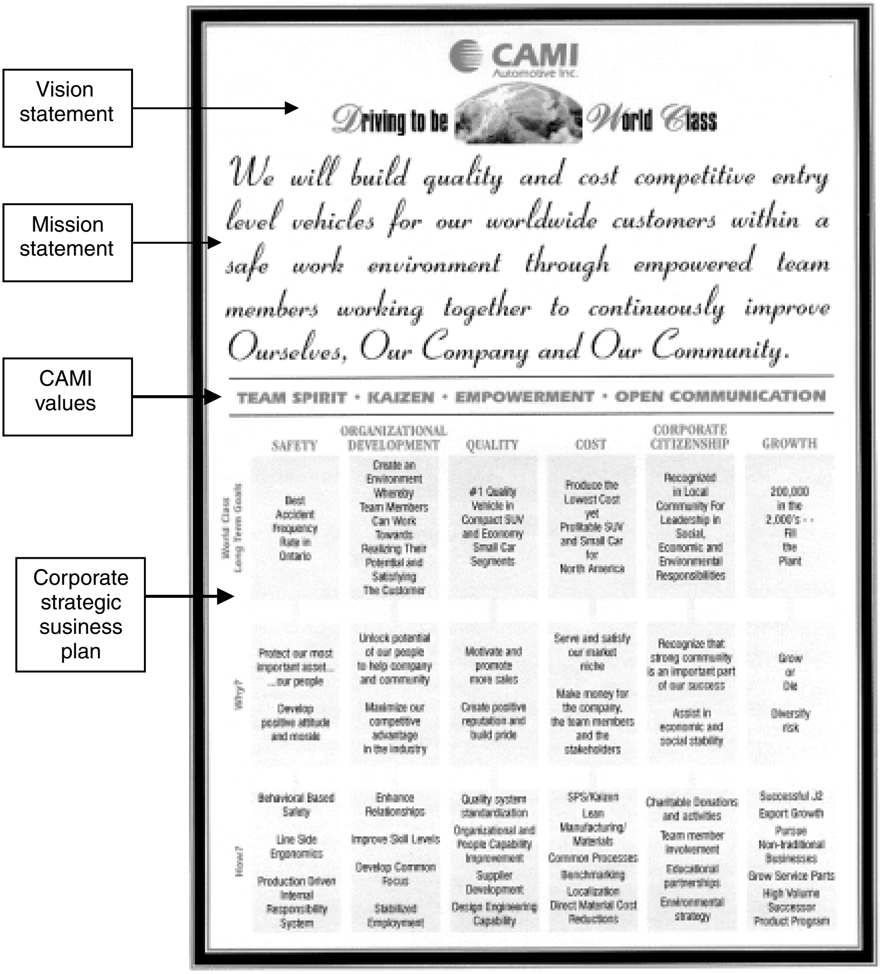
The Suzuki Production System Department plays a very low-key, supportive role at CAMI. It is responsible for the continual training and skill enhancement of our team members, as well as benchmarking internally and externally to improve our application of SPS.

CORPORATE VISION AND MISSION

In 1996, the CAMI executive team established a vision—"Driving to be World Class"—as well as a mission statement designed to give CAMI team members a common focus and direction. The strategic business plan was then designated as the method of achieving this vision (see Fig. 9.9.2).

Corporate Objectives

Each year, CAMI's executive team determines the strategies/objectives for the coming fiscal year. These strategies are designed to complement the Corporate Strategic Business Plan. The annual objectives are designed to progressively drive the organization closer to achieving the vision. The corporate objectives are transferred into the Annual Objectives Implementation Plan (AOIP) and are split into the six categories of the business strategy plan: safety, organizational development, quality, cost, corporate citizenship, and growth (see Fig. 9.9.3). These six categories are core strategies and form the foundation for CAMI's world-class performance.


Vision statement
Mission statement
CAMI values
Corporate strategic susiness plan
CAMI
Automotive Inc.

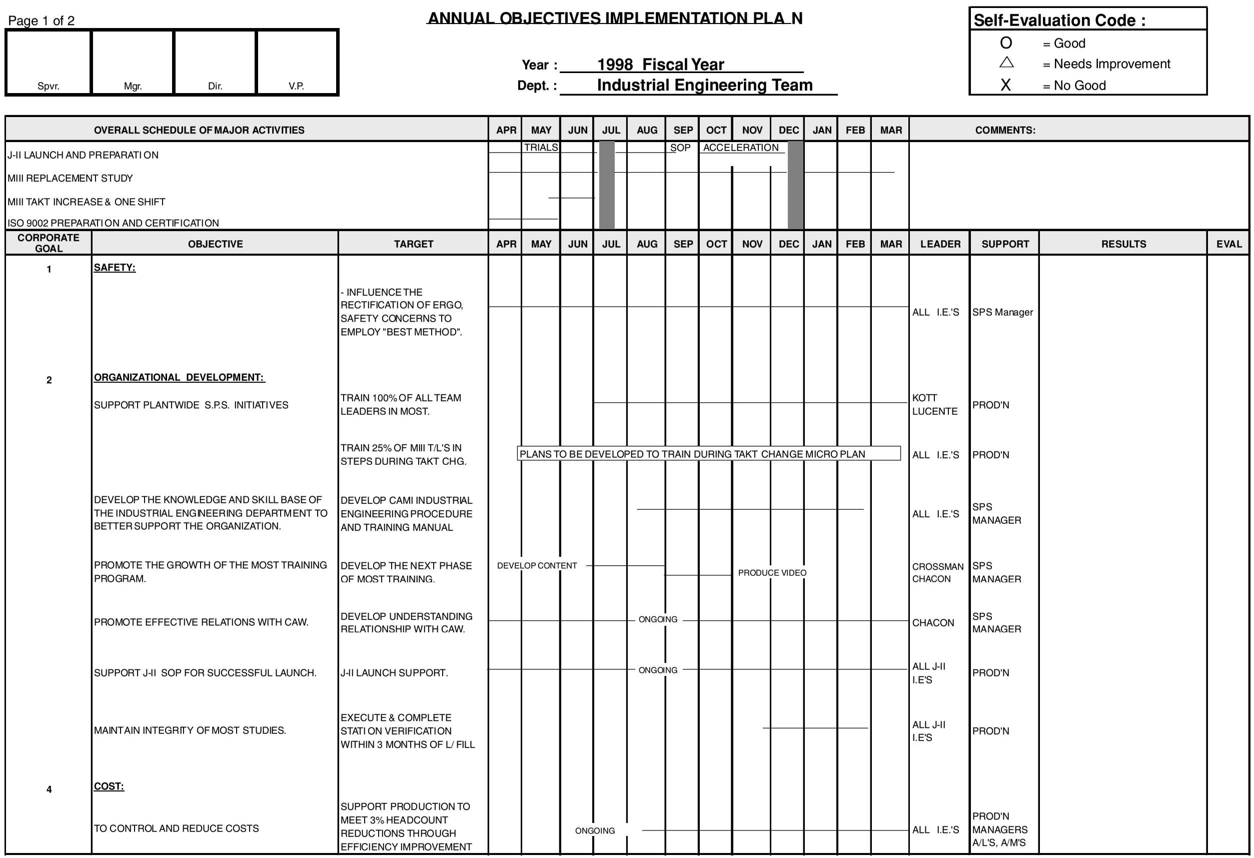
Driving to be World Class

We will build quality and cost competitive entry level vehicles for our worldwide customers within a safe work environment through empowered team members working together to continuously improve Ourselves, Our Company and Our Community.

TEAM SPIRIT · KAIZEN · EMPOWERMENT · OPEN COMMUNICATION

	SAFETY	ORGANIZATIONAL DEVELOPMENT	QUALITY	COST	CORPORATE CITIZENSHIP	GROWTH
World Class Long Term Goals	Best Accident Frequency Rate in Ontario	Create an Environment Whereby Team Members Can Work Towards Realizing Their Potential and Satisfying The Customer	#1 Quality Vehicle in Compact SUV and Economy Small Car Segments	Produce the Lowest Cost yet Profitable SUV and Small Car for North America	Recognized in Local Community For Leadership in Social, Economic and Environmental Responsibilities	200,000 in the 2,000's - - Fill the Plant
Why?	Protect our most important asset... ...our people Develop positive attitude and morale	Unlock potential of our people to help company and community Maximize our competitive advantage in the industry	Motivate and promote more sales Create positive reputation and build pride	Serve and satisfy our market niche Make money for the company, the team members and the stakeholders	Recognize that strong community is an important part of our success Assist in economic and social stability	Grow or Die Diversify risk
How?	Behavioral Based Safety Line Side Ergonomics Production Driven Internal Responsibility System	Enhance Relationships Improve Skill Levels Develop Common Focus Stabilized Employment	Quality system standardization Organizational and People Capability Improvement Supplier Development Design Engineering Capability	SPS/Kaizen Lean Manufacturing/ Materials Common Processes Benchmarking Localization Direct Material Cost Reductions	Charitable Donations and activities Team member involvement Educational partnerships Environmental strategy	Successful J2 Export Growth Pursue Non-traditional Businesses Grow Service Parts High Volume Successor Product Program

FIGURE 9.9.2 Corporate vision/mission/five-year strategic plan.



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Spvr.	Mgr.	Dir.	V.P.

ANNUAL OBJECTIVES IMPLEMENTATION PLAN

Year : 1998 Fiscal Year
Dept. : Industrial Engineering Team

Self-Evaluation Code :
O = Good
△ = Needs Improvement
X = No Good

OVERALL SCHEDULE OF MAJOR ACTIVITIES	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC	JAN	FEB	MAR	COMMENTS:
J-II LAUNCH AND PREPARATION		TRIALS				SOP	ACCELERATION						
MIII REPLACEMENT STUDY													
MIII TAKT INCREASE & ONE SHIFT													
ISO 9002 PREPARATION AND CERTIFICATION													

CORPORATE GOAL	OBJECTIVE	TARGET	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC	JAN	FEB	MAR	LEADER	SUPPORT	RESULTS	EVAL
1	**SAFETY:**																	
		- INFLUENCE THE RECTIFICATION OF ERGO, SAFETY CONCERNS TO EMPLOY "BEST METHOD".													ALL I.E.'S	SPS Manager		
2	**ORGANIZATIONAL DEVELOPMENT:**																	
	SUPPORT PLANTWIDE S.P.S. INITIATIVES	TRAIN 100% OF ALL TEAM LEADERS IN MOST.													KOTT LUCENTE	PROD'N		
		TRAIN 25% OF MIII T/L'S IN STEPS DURING TAKT CHG.		PLANS TO BE DEVELOPED TO TRAIN DURING TAKT CHANGE MICRO PLAN											ALL I.E.'S	PROD'N		
	DEVELOP THE KNOWLEDGE AND SKILL BASE OF THE INDUSTRIAL ENGINEERING DEPARTMENT TO BETTER SUPPORT THE ORGANIZATION.	DEVELOP CAMI INDUSTRIAL ENGINEERING PROCEDURE AND TRAINING MANUAL													ALL I.E.'S	SPS MANAGER		
	PROMOTE THE GROWTH OF THE MOST TRAINING PROGRAM.	DEVELOP THE NEXT PHASE OF MOST TRAINING.	DEVELOP CONTENT							PRODUCE VIDEO					CROSSMAN CHACON	SPS MANAGER		
	PROMOTE EFFECTIVE RELATIONS WITH CAW.	DEVELOP UNDERSTANDING RELATIONSHIP WITH CAW.					ONGOING								CHACON	SPS MANAGER		
	SUPPORT J-II SOP FOR SUCCESSFUL LAUNCH.	J-II LAUNCH SUPPORT.					ONGOING								ALL J-II I.E'S	PROD'N		
	MAINTAIN INTEGRITY OF MOST STUDIES.	EXECUTE & COMPLETE STATION VERIFICATION WITHIN 3 MONTHS OF L/ FILL													ALL J-II I.E'S	PROD'N		
4	**COST:**																	
	TO CONTROL AND REDUCE COSTS	SUPPORT PRODUCTION TO MEET 3% HEADCOUNT REDUCTIONS THROUGH EFFICIENCY IMPROVEMENT			ONGOING										ALL I.E.'S	PROD'N MANAGERS A/L'S, A/M'S		

FIGURE 9.9.3 Example of an Annual Objectives Implementation Plan.

Corporate Annual Objectives Implementation Plan

Each category of the annual corporate objectives is issued to an executive team member to champion. This team member along with the manager of each department will develop more focused objectives for each of their management team members based on their area of responsibility. The Annual Objectives Implementation Plan, illustrating the objectives for all six categories, is issued to every salaried team member at the beginning of the fiscal year. Each individual tracks their progress with respect to each of the objectives on a monthly basis using the Plan-Do-Check-Act (P-D-C-A) format.

Monthly P-D-C-A Report

This is a planning and self-assessment tool that ties an individual's performance directly to the elements of the Corporate Strategic Business Plan. See the subsequent section on follow-up systems for more information.

THE IMPLEMENTATION OF THE SUZUKI PRODUCTION SYSTEM

Training

The Suzuki Production System Department's main role is to continually raise the awareness level of the elements of the system and the benefits of using it to structure all activity. This is coupled with facilitating hands-on projects aimed at enhancing application skills throughout the company. This is a constantly evolving, never ending process, and it is expected (supported by observations) that the stages of an individual team member's training will be followed by self-initiated improvement projects and adherence to the principles of the system. The training sessions will diminish in importance, as the system becomes more of a natural reflex in the plant. The Suzuki Production System Department is careful not to take ownership of any initiatives that are undertaken during the training so that the system will remain after the department's involvement ends. We are currently running the following programs.

Production Associate SPS Training. A one-week, largely hands-on program that introduces team members to the principles of SPS with heavy emphasis on the benefits of using the system to direct day-to-day activities. A direct link between the team member's job and the corporate strategic plans are stressed. The team members complete a one-day 5S audit and project, during which they are taught how to read and verify a MOST® study, isolate a problem in their team, and go through the CAMI problem-solving process to resolve it.

Team Leader SPS Training. Team leader partners from opposite shifts (an important factor to ensure buy-in) spend three weeks together to learn the theory of the Suzuki Production System and, more important, how to implement its elements so that they can better support their teams. The first week is structured around 5S. The team leaders audit each station and common team areas and undertake projects to eliminate all gaps. Standardized work is the main subject for the second week. Following an introduction to the benefits of this element, an industrial engineer trains the team members in the basics of the MOST system. Then they spend several days verifying the MOST studies for their workstations and discuss any discrepancies with industrial engineering. Empowering team leaders to ensure the studies are accurate was a watershed event at CAMI. It eliminated mistrust on the floor and gave them a tool to solve process bottlenecks and design process layout changes.

During the third week, the team leaders work together to identify a problem within their team and solve it using the CAMI problem-solving process, then the results are presented to management.

Team Leader Business Proposal Project. Following the three-week SPS training, the team leader pairs submit a business proposal to their area leader that outlines a problem that they want to eliminate, the benefits to CAMI (as well as the estimated cost), and the support groups that they will need to involve. Twice a year, each pair is freed from their normal duties to work on team problems.

This program not only eliminates problems and keeps the team leaders' skills honed, it also strengthens the working relationships between the production team and the support departments. It reinforces the principle that the Suzuki Production System focuses all support on the team member.

Area Leader SPS Gap Analysis. All area leaders (frontline supervisors) from one shop jointly discuss the role that they *should* play for each element of the Suzuki Production System. The next step is to assess how well the group is performing for each item and determine where gaps exist. They then decide on group projects that are designed to eliminate/reduce the gaps. Presentations to the executive team and managers are scheduled so that successful implementations can be applauded and supported. These also function as benchmarking opportunities for other departments.

Area Leader P-D-C-A Problem-Solving Projects. Opposite shift area leaders are paired for one week to investigate the P-D-C-A monthly report for another area, identify a gap between target and actual, determine the root cause, and implement solutions. This program was designed to yield several benefits:

- It resolves a production problem.
- Area leaders become more skilled in the problem-solving process.
- Because the target area was unfamiliar, the area leaders are forced to spend more time doing root cause analysis. (This stage is usually minimized when leaders are familiar with the problem.)
- It reinforces the recommendation that the P-D-C-A report that *tracks* performance toward corporate goals should be also used as a *tool* to launch improvement projects.

Assistant Manager Training. Suzuki Production System is coupled with project management training for this level of our organization. During this program, they are expected to identify a critical gap in the performance of their shop and design a major project, which will move them closer to the corporate strategic target. The assistant manager then involves all of his or her area leaders who must implement this plan across the shop through the team leaders. This has several benefits:

- Major issues are addressed informally in the shop.
- Skills of the area leaders and team leaders are utilized.
- The roles of assistant manager, area leader, and team leader are better defined and reinforced.

Kaizen Event. Cross-functional teams are put together to quickly address critical problems that are negatively affecting the safety of team members, quality of the product, or uptime. They follow the CAMI problem-solving process and involve the production team members at all stages.

Support Department Gap Analysis/Project. This is identical in structure and outcome to the area leader program.

Support Department Problem Solving. Team members from the support departments (engineering, maintenance, quality, etc.) join the team leaders for their problem-solving projects. This reinforces the idea that the production team members are the focus of all support, and gives them an opportunity to contribute their expertise to the project.

REACTIONS TO THE TRAINING

Four years ago, our first attempts to strengthen the Suzuki Production System failed immediately. With little communication and team involvement, "strangers" descended on a production team to solve its problems. Predictably, cooperation was nonexistent and all implemented improvements had a very short life span.

The Suzuki Production System Department was formed. Two area leaders (production supervisors) and six production associates (hourly team members) designed and facilitated a three-week program to give the team leaders the tools and experience to better support their team members. The program emphasizes the benefits of a production system and connects every aspect of the individual's job to the corporate objectives.

The change was painfully slow. The first positive sign was that the team projects taken on by the team leaders always succeeded. Rough spots after implementation were seen as further kaizen opportunities rather than reasons for rejection (as with the forced improvements).

However, the activity was still confined to the weeks of the SPS training session. It was two years before activities associated with the elements of the Suzuki Production System automatically became part of everyone's job.

The steps to success are (1) educate and train team members, (2) empower them to identify areas that need improvement and implement a change, (3) provide all necessary support, and then (4) stand back!

Follow-up/Audit Systems

Numerous follow-up systems are employed to ensure accountability, consistency, and integrity in the system. These systems are linked between the Suzuki Production System and corporate strategy plans with the focus on supporting the shop floor operator. Two types of follow-up systems are in place.

Type 1—Daily Maintenance of the System. This is often recognized as the daily pulse taking. Type 1 systems are done at the team level. It drives ownership and responsibility to the production associates and reinforces that everyone contributes to the achievement of the corporate objectives. The following represent examples of some type 1 systems in place:

- Various measurements at the team leader level—audits
- Quality control nonconformance report
- Team scrap report
- Tracking and monitoring of consumable usage

Type 2—Long-Range Systems. Long-range systems focus on the annual goals, objectives, and vision of the organization. It is extremely important that these systems have a built-in mechanism to constantly remind the team member of what needs to happen and by when. The following represent examples of some type 2 systems in place:

Annual Objectives Implementation Plan. This is developed between the supervisor of each department and his or her immediate leader. The annual objective will support the corporate objectives for the year.

Employee Development Review (EDR). This is the set of objectives that all salaried team members receive at the beginning of the fiscal year. The department supervisor will review the EDR with each team member after six months and then once again as a final review at the end of the fiscal year. The objectives on the EDR include the following:

- The department's Annual Objectives Implementation Plan.
- Other objectives to strengthen the skill and knowledge base of the team member.

CASE STUDY: AN EFFECTIVE PRODUCTION SYSTEM FOR THE AUTOMOTIVE INDUSTRY

- CAMI values, which are team spirit, kaizen, open communication, and empowerment.
- Growth/coaching plan. This represents the plans to make the team member successful in achieving the EDR objectives and the short-term goals.

Monthly Plan-Do-Check-Act Report. This is a planning and self-assessment tool that ties an individual's performance directly to the objectives of his or her EDR. This is done on a monthly basis by each salaried team member and reviewed with his or her direct supervisor. The activity of all team members is to self-monitor action plan performance through the P-D-C-A process. The P-D-C-A reporting format provides a tool that allows team members to evaluate their own personal progress towards achieving objectives in a structured, standardized manner. All team members report out on a monthly basis on their progress in achieving their annual objectives. It is important to ensure that successes, as well as areas for further improvements, are highlighted. This system serves as a constant reminder to each team member of his or her EDR objectives. It ensures that the objectives are not forgotten. By taking a close look at the P-D-C-A format, it is evident how it relates to the Suzuki Production System. Every objective on a P-D-C-A is associated with one or more of the pillars of the Suzuki Production System. It is also the *standard* format for all team members to report monthly their progress towards their objectives. By using this common system, any team member at CAMI can recognize another individual's current status and make a determination as to whether the goal has been achieved or assistance is required in achieving the specific objectives (see Fig. 9.9.4).

Six-month AOIP Report-Out to the Executive Team. Six months into the fiscal year, each department manager has a report-out to the executives on the status of the department's Annual Objectives Implementation Plan.

President's Weekly SPS Audit. On a weekly basis, the president along with the executives will tour a department at the plant. The manager of the department presents changes that have been implemented toward strengthening the Suzuki Production System environment. The focus is always on the shop floor. This also sends a message as to the importance of the Suzuki Production System. At the end of the presentation, the president summarizes his observations and provides comments and recommendations towards the next step.

Corporate Quarterly Rollout. Each quarter of the fiscal year, production will stop for one hour for a corporate update by the executives to all team members. The purpose of the rollout is to provide a greater means of communicating our state of affairs to the workforce. The executive team members constantly emphasize the Suzuki Production System.

Tracking Mechanisms. There are numerous tracking mechanisms and measurements that have been implemented that support principles of SPS such as standardization, quality in station, and kaizen. The tracking mechanisms provide a visual management tool to better understand our progress. Tracking mechanisms also provide a baseline for benchmarking. Future targets are based on the findings of the benchmarking studies.

Role of the Industrial Engineer

With the implementation of the Suzuki Production System, the role of the industrial engineer had to change, moving away from the traditional role. At CAMI, production team members use the MOST study to manage their team's line balance and kaizen, and to develop and implement the plans for takt (line speed) changes. The following sections illustrate some of the changes that the industrial engineering team implemented to better support the production associate.

Standards for the Industrial Engineer. To promote consistency, accountability, and integrity, the following standard operating procedures were developed for the industrial engineers to follow:

- Guidelines and checklists for all CAMI team members to identify potential kaizen improvements

J. Chacon OCT. 3 0, 1998 I.E. Supervisor	S.P.S. Manager	Director

OCTOBER OBJECTIVE REVIEW
1998 FISCAL YEAR
INDUSTRIAL ENGINEERING TEAM

Self-Evaluation Code	
m	= Good
s	= Needs Improvement
5	= No Good

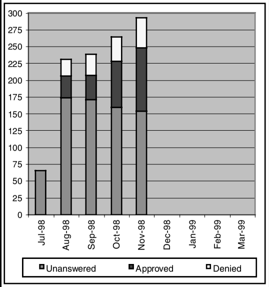
Corporate Goal	OBJECTIVE	TARGET	RESULTS	EVAL.	PROBLEM & ANALYSIS	ACTION (NEXT STEP)
2	ORGANIZATIONAL DEVELOPMENT					
	DEVELOP THE KNOWLEDGE AND SKILL BASE OF THE INDUSTRIAL ENGINEERING DEPARTMENT TO BETTER SUPPORT THE ORGANIZATION.	DEVELOP CAMI INDUSTRIAL ENGINEERING PROCEDURE MANUAL.	8 OF 12 SECTIONS OF THE MANUAL ARE COMPLETE. ON SCHEDULE	○	– NO PROBLEMS ENCOUNTERED.	– CONTINUE TO WORK ON THE MANUAL TO MEET THE FEB DEADLINE.
	SUPPORT J-II SOP FOR SUCCESSFUL LAUNCH	SUPPORT J-II TRUCK LAUNCH.	- CONTINUE TO SUPPORT PRODUCTION IN ALL SHOPS; VERIFICATION, LINE BALANCE, BUYOFFS, RACKING.	○	– NO PROBLEMS ENCOUNTERED.	– CONTINUE ON-GOING SUPPORT, MORE EMPHASIS ON KAIZEN.
	MAINTAIN INTEGRITY OF MOST STUDIES	EXECUTE & COMPLETE STN VERIFICATION BY DUE DATES IN ALL SHOPS.	- VERIFICATION COMPLETE IN STAMPING. ON SCHEDULE IN WELD, PAINT AND ASSY CAR. ASSY TRUCK WILL COMENCE IN NOVEMBER.	○	– NO PROBLEMS ENCOUNTERED.	– CONTINUE ON SCHEDULE.
4	COST:					
	TO CONTROL AND REDUCE COSTS	SUPPORT PRODUCTION TO MEET 3% HEADCOUNT REDUCTIONS THROUGH EFFICIENCY IMPROVEMENT.	COMPLETED TWO HEADCOUNT REDUCTIONS IN THE PAINT DEPARTMENT THIS MONTH. SEVERAL PLANS ARE IN DEVELOPMENT STAGE IN ASSEMBLY MIII. ON SCHEDULE.	○	– NO PROBLEMS ENCOUNTERED.	CONTINUE TO SUPPORT PRODUCTION TO ACHIEVE THEIR 3% HEADCOUNT REDUCTION PLANS.
5	GROWTH					
	ENSURE DFM/A; FLEXIBILITY AND EASE OF ASSEMBLY FOR THE OPERATOR	DOCUMENT, TRACK AND MONITOR DESIGN CHANGE PROPOSALS (D.C.P.) TARGET - 60% APPROVED SUCCESS RATE.		▲	– MORE INPUT FROM THE CAMI TEAM IS REQUIRED. – MORE EMPHASIS IS REQUIRED ON IDENTIFYING OPPORTUNITES TO REDUCE COSTS AND SIMPLIFY THE BUILD PROCESS.	– MORE FOCUS WILL BE PUT IN THE NOVEMBER. – REQUIRE MORE INTERACTION WITH THE DESIGNERS TO CHANGE THE STATUS FROM UNANSWERED TO APPROVED

FIGURE 9.9.4 Example of a monthly Plan-Do-Check-Act report.

CASE STUDY: AN EFFECTIVE PRODUCTION SYSTEM FOR THE AUTOMOTIVE INDUSTRY

- Procedure for implementing efficiency improvements
- Procedure for developing a time standard
- Procedure for communicating changes of a time standard to production
- Procedure for a production associate to dispute a time standard
- Procedure for handling time standard disputes
- Procedure for verifying a time standard
- Strategies to increase efficiency in takt (line speed) changes

Decentralized Industrial Engineering Department. To better foster teamwork and increase the skill and knowledge base of the pilot teams, the Industrial Engineering Department was decentralized. The industrial engineers (IEs) now reside in the same room as the production pilot team members that they support.

Engineering Document Versus a Floor Document. In the past, a MOST study was more of an engineering document than a floor document. The study was written in a way that was efficient for an IE to generate. However, the study could not be understood by the most important user of the information: the production associate.

To focus on floor-driven functions to better support the production associate, the industrial engineering team redesigned the MOST study to be user friendly. This is very important because the studies are posted at every team area. The new format is based on a standard sequential process using the terminology familiar to the production associates. Care is taken to describe each operator action to more clearly reflect the standard. A study now takes more time to generate; however, it can be more easily understood by the operator. This method has resulted in higher trust levels among the hourly team members.

MOST Training. MOST is one of the modules in the Suzuki Production System training. It is facilitated by the industrial engineer responsible for supporting the trainees' department. The trainees are not certified, but gain a strong working knowledge of the method. During the two days following the training, each trainee will review each line of the MOST study, element by element, for each of the workstations they are responsible for. This is done to determine if the study is a true representation of the standardized process on the floor. Any discrepancies are documented. The industrial engineer meets with the trainees to resolve the discrepancies. The training has been very successful. It has helped team leaders increase their level of ownership of the studies. They also understand the need to have up-to-date and accurate studies that they can understand and defend. The training also promotes improved communication, increased integrity/trust, and confidence levels.

Accuracy Level of the MOST Studies. Preserving the integrity and the accuracy level of the MOST studies is extremely important. This is crucial in an environment such as CAMI's where production process changes occur on a daily basis. Production process changes occur due to line balance (to meet market demands), and ergonomics and engineering improvements. The team leaders implement the process changes. For the change to be successfully implemented, it must be documented on a process change request (PCR) form. The team leaders, area leaders, and assistant managers from both shifts, and the department manager for quality and safety must approve the change. Once approval is obtained from all parties, the form is sent to industrial engineering for approval. The change(s) will be approved provided there is an efficiency improvement. Once approved, the MOST study is revised. A MOST study update sheet is prepared by the industrial engineer outlining the new standard time, the change(s) to the study, and kaizen recommendations. These two documents along with the PCR form are issued to the pilot team. The next step is to prepare a station graph representing the revised MOST study. The station graph provides a visual depiction of the station-weighted standard time, the line speed, operator load line, and the impact of all models at the workstation. Once complete, the pilot team member will forward the PCR, the revised MOST study, and the new station graph to the team leader. These documents are then posted in the team area.

Regular MOST Study Follow-up. The industrial engineer has a scheduled meeting with both shift team leaders once a month to review any changes in the MOST study. The follow-up meeting promotes team building, effective communication, accountability, and ensures accurate studies for each workstation.

Weekly Meetings with the Production Standards Representative. Each week the supervisor of industrial engineering meets with the union's production standards representative. The purpose of the meeting is to bring one another up to date on production concerns and progress with respect to production standards. The meetings effectively promote an excellent relationship. Each week issues and corrective countermeasures are discussed. The meetings also promote a proactive approach to new model planning.

Final Note. Results of recent benchmark studies indicated that an automotive manufacturer similar in size/capacity to CAMI would have approximately 22 industrial engineers. At CAMI, there are 6 industrial engineers servicing and supporting all plantwide operations. This low number of industrial engineers is due to the level of empowerment of the hourly workforce and the Suzuki Production System environment.

RESULTS AND CONCLUSIONS

By focusing on the Suzuki Production System, CAMI is improving its competitiveness at a rapid rate. The system has allowed us to focus and improve in many areas. The following represent some of CAMI's achievements:

- High level of flexibility. Due to market demands, CAMI has been averaging four takt (line speed) changeovers per year with no impact to production. This is due to standardized procedures, SPS training, and a highly empowered hourly workforce. The automotive industry is constantly changing. To become world class, it is important for an organization to be flexible and adapt to the demands of the market.
- Excellent results in our Employee Suggestion Program. In 1997, 11,150 suggestions were submitted (6.01 suggestions per employee) at a 92.6 percent acceptance rate; 80.2 percent were actually implemented, which resulted in a $1.6 million savings.
- Third-best safety record for an automobile assembly plant in Ontario (total 13).
- Environmental improvements—96.4 percent of solid waste is recycled. In 1994, CAMI was the winner of the Outstanding Large Business Category award from the Recycling Council of Ontario.
- All team leaders and area leaders (supervisors) are trained in MOST so that they can decipher a study. All studies are posted in the team area on the shop floor.
- Standard time disputes have decreased from 20 per month in 1995 to a total of 4 in 1998. Confidence levels in the MOST studies are extremely high. This is due to the MOST training and subsequent involvement of team leaders in the verification process with the industrial engineers.
- In 1997, CAMI implemented the Performance Incentive Program. This program provides all CAMI employees with a payout for meeting set targets in the areas of safety, quality, productivity, and cost. This program fully reinforces the link between the individual and corporate objectives.
- Annual 3 percent Headcount Reduction Program. This is an annual objective for each production manager. The progress is tracked and monitored on a monthly basis via the PDCA format.

- Ongoing team-generated kaizen projects illustrate that the Suzuki Production System is successfully entrenched on the shop floor.
- ISO certification in 1998.
- J-II (Chevrolet Tracker and Suzuki Vitara) successfully launched. The hours per vehicle were reduced by 25 percent through vigorous DFM/A (design for manufacturing/assembly) sessions; 1100 were generated with a 66 percent success rate.
- Synchronous carts at the workstation. In 1995 there were only a handful of synchronous carts on the shop floor. By 1998 there were well over 150 synchronous carts. The carts are designed and built by the teams with assistance from the kaizen shop. The carts are simple and nonpowered so that they do not contribute to downtime. The purpose of the carts is to reduce non-value-added elements of the job.
- Rebirth of the Suzuki Production System, which has improved communication within the organization. It has also increased the feeling of ownership in all team members. The level of training for the shop floor operators has resulted in a more empowered workforce, increased integrity of the overall systems, and higher confidence levels.

CAMI's commitment to the Suzuki Production System has provided the ability to build a quality vehicle at a low cost in a safe working environment. This ability is one of our greatest competitive advantages. The SPS philosophies simplify our operation to more effectively compete worldwide by using the best practices in the global automotive industry. This is evident by the results achieved from the aggressive goals for improving workplace safety, cost efficiency, quality, and productivity.

The reintroduction of SPS over the past three years has been extremely challenging. Five years ago, CAMI was becoming a traditional North American automotive plant. We are now recognized as a leader in the automotive manufacturing industry. We are on our way to "Driving to be World Class."

As an organization, we have a long way to go to achieve our vision, and as a result, are less willing to compromise the gains we have made to date. These past and future challenges make CAMI the determined organization that it is.

FUTURE VISION

We are confident that CAMI will achieve its vision of being world class, as long as we continue to hold to the course of our long-term corporate strategic plan and our six key corporate objectives. The challenge going forward is to ensure that we continue to follow the philosophies of the Suzuki Production System. The dynamics of the Suzuki Production System will support all team members in achieving their goals and objectives. The future vision for the Suzuki Production System is to continue to evolve. This includes tailoring training to higher levels in management and supporting groups to enable them to create their department's future state. The future state includes changing roles and responsibilities so they may better support the team member. This is possible by simplifying processes/procedures, and is also due to the level of empowerment that the shop floor team leaders and team members assume. An example of this is empowering the team members to develop their own MOST studies: the industrial engineer's role changes to that of a coach and an auditor, and an approver of the MOST studies. The industrial engineer will have more time to identify and develop strategies to nurture and assist production to continually increase its skills and knowledge base concerning the elimination of waste and efficiency gains.

The key to CAMI's success is, and will continue to be, the Suzuki Production System. By focusing on this philosophy, CAMI will achieve its vision by becoming a leading world-class manufacturer meeting the global market's demand for a high-value, high-quality, competitively priced vehicle.

ACKNOWLEDGMENT

We would like to thank Phil Johnston who was hired as vice president of production at CAMI Automotive in 1993. He immediately recognized the need for CAMI to go back to basics and reintroduce the Suzuki Production System.

BIOGRAPHIES

Joe Chacon, B.A., CET, is the supervisor of industrial engineering at CAMI Automotive Incorporated based in Ingersoll, Ontario, Canada. He has served on the board of directors for the Canadian Society of Industrial Engineers. He is currently a member of the Ontario Association of Certified Engineering Technicians and Technologists.

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Source: MAYNARD'S INDUSTRIAL ENGINEERING HANDBOOK

S · E · C · T · I · O · N · 10

LOGISTICS AND DISTRIBUTION

LOGISTICS AND DISTRIBUTION

CHAPTER 10.1

INDUSTRIAL ENGINEERING SUPPORT FOR MATERIALS MANAGEMENT

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This chapter describes the role of the industrial engineer in supporting materials management. The potential scope of this support spans the supply chain from supplier through production and distribution. Industrial engineering is presented as the principal discipline involved in physical planning for materials transportation: from suppliers to points of storage or use; for materials handling in receiving and shipping and between processing operations; and for materials storage (purchased, work in process, and finished goods). The industrial engineer may need to work with the company's suppliers, helping them to adopt new procedures and systems. And, to be effective, the industrial engineer must cooperate with and understand the objectives of others in procurement, transportation, production planning and control, warehousing, and information systems.

BACKGROUND

Scope of Materials Management

Since the 1970s, materials management has referred to the group of functions that manage the complete cycle of material flow:

- Purchase and internal control of production materials
- Planning and control of work in process
- Warehousing, shipping, and distribution of finished products

Under this definition, materials management includes the functions of procurement, inventory and demand management, production planning and control, distribution, logistics, and supply chain management. Managers and professionals working within these functions make the following recurring decisions:

- Choice of supplier
- Use of logistics service companies
- When and how much to order
- Ownership of inventory
- Production policies: make to order; make to stock
- When and how much to produce
- Location and level of finished inventories
- Information processing requirements

These materials management decisions involve considerations and physical outcomes that must be planned and accommodated in daily operations. The most important are as follows:

- Supplier capabilities and locations
- Size, content, and frequency of inbound deliveries
- Purchased material inventory levels
- Production run frequencies and lot sizes
- Work-in-process inventory levels
- Warehouse locations
- Warehouse materials flows: receiving and putaway; order picking and shipping
- Finished-goods inventory levels
- Locations, frequencies, and formats for data collection and information processing

Key Trends in Materials Management

Modern materials management strives to keep inventory very low while still providing very high levels of product and material availability and very fast response to changing or unexpected demand. In general, these goals are being achieved with greater flexibility, speed, and capacity in supply, production, transportation, and distribution.

More volume is being concentrated among fewer and more-capable suppliers. Receipts are preinspected or certified and ready to use. Supplier replenishments to production are more frequent and, in smaller loads and lots, matched to rates of consumption. In some cases, suppliers may add more value or even bypass production, drop-shipping a completed product directly to the customer.

In manufacturing, items are produced more frequently in smaller lots, often within manufacturing cells dedicated to particular parts or products. In repetitive assembly, inbound parts may be sequenced and kitted by a logistics service company to match the planned assembly sequence. More parts are being delivered directly to points of use, often in returnable containers.

In distribution, more incoming goods are being cross-docked—moving directly to outgoing orders or lanes without resting in storage. In retail distribution, more shipments are direct to retail outlets in floor-ready condition. Finished goods are being reduced as more products are made to order and shipped directly to customers. More companies are attempting to postpone finishing or customizing operations, moving them from plant to distribution center and performing them to customer order, immediately prior to shipment. With increasing frequency, these operations may be performed by a logistics service company that also receives and merges purchased-complete items to deliver a customer's full order.

INDUSTRIAL ENGINEERING SUPPORT FOR MATERIALS MANAGEMENT

More effective information systems are providing upstream operations with earlier or even instant visibility of downstream consumption or requirements. With bar coding and other forms of automatic identification and data capture, materials are being tracked and their status reported at every step between raw material supply and final sale or consumption as finished products.

Role of the Industrial Engineer

The industrial engineer plans the methods, human resources, space, and equipment needed to implement materials management decisions. Working with materials management, the industrial engineer translates intended targets, policies, and procedures into effective physical systems of production, material handling, warehousing, and transportation. In this role, the industrial engineer engages in a variety of supporting activities, including the following:

- Supplier planning
- Schedule and order planning
- Transport load planning
- Material handling and storage analysis
- Process and methods improvement
- Work measurement
- Information systems integration

Figure 10.1.1 summarizes the key decisions of materials management, the physical considerations and consequences, and the supporting activities and analyses that are the responsibility of the industrial engineer.

SUPPLIER PLANNING

In a well-designed materials management system, each supplying operation delivers its output in the form and quantity desired by its customer operation—ideally at a rate that matches the rate of consumption. If the customer needs frequent deliveries of small lots, the supplier's first challenge is to produce regularly in short runs. If the supplier makes infrequent, longer runs, then inventory is created, and the small lots must be picked from stock to provide the desired delivery pattern. The supplier's second challenge is to package in the physical form desired by the customer. Ideally, the supplier's last operation will place the product directly into the container desired by the customer, thus eliminating the need to rehandle or repack downstream or to work from a poorly sized or configured package or container. Finally, the supplier must ship or deliver with the desired frequency.

The supplier's ability to do these things will have a controlling impact on downstream receiving, material handling, storage, floor space, and operator productivity. For this reason, the industrial engineer must understand the supplier's process and material handling capabilities and be prepared to help if the supplier is not performing as desired. This will require a site visit and the development or review of operation process charts. Key questions to be answered include the following:

- What is the current lot size and run frequency? What is the minimum economic lot size?
- What can be done to drive it down?
- How efficient is the setup or changeover process? Has it been studied and engineered? Can it be improved so that frequent short runs will be less costly?

Materials Management Decisions	Key Issues & Physical Considerations	Industrial Engineering Support
• **Choice of supplier.** Typically based on: - Quality. - Service. - Price.	• **Supplier capabilities.** - Processing & assembly. - Need for incoming inspection. - Lot sizes & run lengths. - Lead/response time. • **Supplier locations & distances.** - Transport modes and transit times.	• **Supplier planning.** Opportunity to: - Improve capabilities. - Reduce/eliminate need for inspection. - Reduce lot sizes & lead times. - Use more appropriate containers. - Change container & package quantities.
• **Use of logistics service companies.** Typically used for: - Regularly scheduled supplier pickups. - Consolidation of incoming loads. - Sequencing of incoming materials. - Kitting or assembly of multiple parts or items. - Storage of materials until time of need.	• **Size & frequency of supplier shipments.** - Replenishment pattern: scheduled or as needed. - Standard or variable quantity. - Receipt quantity: typical & range. • **Inbound delivery content & frequency.** - Vehicle types and load sizes. - Arrival times. - Container & package types & sizes. - Load & unload sequences. - Readiness for delivery to point of use.	• **Schedule & order planning.** - Opportunity for regularly scheduled pickups (milk runs). - Receiving capacity & schedule. - Use of kitting & sequencing. - Container & package quantities. • **Transport load planning.** - Cube & weight of supplier shipments. - Capacity & utilization of shipping vessel/vehicle. - Route structure. - Loading & unloading sequence & times.
• **When and how much to order.** Typically based upon: - Demand & variability. - Length & variability of lead times between supplier and point of consumption or sale. - Supplier's production policies: Make to order or make to stock. - Inventory ownership & carrying cost. - Transportation cost. - Order processing & receiving cost (labor and expense). • **Ownership of inventory.** Between supplier's production and point of consumption or sale.	• **Purchased material inventory levels.** - Storage location: origin, destination, or in-between at service company. - Expected on-hand quantities: Minimum, maximum, average.	• **Material handling & storage analysis.** For purchased parts & materials. - Unloading & staging equipment. - Staging & receiving space required. - Receiving methods & procedures. - Handling methods for putaway or direct delivery to point of use. - Where to store: Point of use or central. - Storage methods, equipment, & space. - Layouts of receiving & storage areas. - Work measurement & standards. - Crew sizes & labor requirements.

<table>
<tr>
<td rowspan="3">• **Production policies.**
Make to order or make to stock.
Typically determined by:
- Location of customers and points of consumption or sale.
- Customer's lead-time expectations.
- Demand level, pattern, and variability.
- Process characteristics and equipment.
- Lead times on purchased materials.
- Time required to set up and produce.
- Order processing & setup cost (labor and expense).
- Inventory ownership & carrying cost.

• **When and how much to produce.**
- Production policies: to order or stock.
- Location & level of finished inventories.
- Rate and pattern of consumption.</td>
<td>• **Run frequency.**
How often to produce an item, part, or product.

• **Lot size or length of production run.**
What quantity to produce:
- Typical range or quantity.
- Minimum quantity.</td>
<td>• **Process & methods improvement.**
- Setup reduction.
- Improved procedures.
- Tooling & fixturing.
- Capacity & availability of equipment.
- Use of manufacturing cells.
- Process simplification & integration.
- Yield improvements.</td>
</tr>
<tr>
<td>• **Work-in-process inventory levels.**
- Expected on-hand quantities: Minimum, maximum, average.
- Quantity of issue: minimum & typical range.</td>
<td>• **Material handling & storage analysis.**
For work-in-process between operations.
- Container types & sizes.
- Material handling methods.
- Staging & storage locations.
- Storage methods & equipment.</td>
</tr>
<tr>
<td rowspan="2">• **Warehouse locations.**
- Distances from plants.
- Distances to customers & service areas.

• **Receiving & putaway quantities.**
Maximum & typical ranges.

• **Finished-goods inventory levels.**
- Expected on-hand quantities: Minimum, maximum, average.

• **Order-picking quantity.**
Minimum & typical ranges.</td>
<td rowspan="2">• **Material handling & storage analysis.**
For finished-goods distribution.
- Packaging & palletization.
- Transport equipment & load planning to warehouses & delivery to customers.
- Warehouse receiving & staging methods, equipment, and layout.
- Handling methods for putaway or direct flow to outbound shipment staging.
- Storage & order-picking methods & equipment.
- Warehouse space & layout.
- Work measurement & standards.
- Crew sizes & labor requirements.</td>
</tr>
<tr>
<td>• **Location & level of finished inventories.**
Typically based upon:
- Location of customers and points of consumption or sale.
- Customers' lead-time expectations.
- Demand level, pattern, and variability.
- Production policies: to order or stock.
- Transport costs, times, and variability.</td>
</tr>
<tr>
<td>• **Information processing requirements.**
Through procurement, production, storage, transportation, and consumption.</td>
<td>• **Frequencies & locations.**
Of data capture, transfer, processing and reporting.

• **Standards.**
For labeling, formatting, transmitting, and processing.</td>
<td>• **Information systems integration.**
- Data collection methods & devices.
- Labeling & automatic identification.
- Network planning: wired & wireless.
- Location of computers, displays, & peripheral devices.</td>
</tr>
</table>

FIGURE 10.1.1 Industrial engineering support for materials management. *(© 1999. Richard Muther & Associates.)*

- Is the processing machinery suitable for short runs? Is different equipment required?
- Is the process statistically capable of meeting specified quality? Is it under control?
- Can production be reorganized, perhaps into cells that could be scheduled by consuming operations?
- Can the supplier pack directly into the desired container?
- Is the desired container properly sized with respect to the supplier's operations?
- Does the supplier experience information delays that make it difficult to respond to the ordering or demand pattern?

The industrial engineer should be prepared to help the supplier answer these questions and even to work with the supplier to make desirable improvements. The company's buyer and quality personnel may assist the supplier with process capability and quality, but unless they are also industrial engineers, they will typically lack the ability to help on matters relating to setup, containers, material handling, and the layout of plant and equipment.

The industrial engineer should also understand the transportation time associated with a supplier's location. The longer and the more variable this time, the more purchased inventory will need to be carried at the consuming location. Recurring weather or seasonal factors, traffic and road conditions, customs and border delays must all be considered when establishing a realistic transportation lead time.

Suppliers may offer to manage consigned inventories at a customer's plant or warehouse. In this situation, the inventory is replenished at the supplier's discretion. This should not reduce the industrial engineer's interest in the supplier's internal processes and transportation lead times, since the cost of any excessive inventory or material handling is still present in the price of the delivered materials.

ORDERING AND SCHEDULING

Along with physical characteristics of the materials themselves, ordering patterns and schedules will determine the methods, human resources, and facilities required for transport, receiving, handling, and storage. Frequent small orders in standard quantities, with regularly scheduled deliveries, are generally more desirable than infrequent and irregular large orders and deliveries.

Large receipts require more space and often larger pieces of handling equipment. Irregular arrivals of large orders also lead to bottlenecks in receiving and delays in processing materials. These delays, in turn, can have consequences downstream, leading to stock-outs and costly corrective actions.

Irregular, nonstandard packaging and container quantities play havoc with handling and storage and require sizing for worst-case conditions. This is wasteful of space.

Ideally, ordering and scheduling will spread deliveries evenly throughout the shift, day, and week to avoid peak bottlenecks and idle times in receiving. The industrial engineer should work with procurement and information systems personnel to make sure that delivery dates are not arbitrarily set for Mondays or Fridays by default.

If several suppliers are close enough to one another, it may be practical to construct a regularly scheduled route to pick up their respective shipments. Such routes—often referred to as *milk runs*—can offset the otherwise higher transportation costs of independent shipments, especially if they are small and frequent. Milk runs can be performed by transportation companies or by a logistics service company. The latter may have warehousing capabilities and can be used as a buffer between suppliers and a receiving plant or warehouse location. Typically, the service company picks up or receives suppliers' shipments and then holds and handles them in ways that smooth their delivery and lower their processing costs at destination plants and warehouses. The inventories being held may be consigned and still owned by the suppliers. Generally, the service company does not take title to (or ownership of) the inventory. However, ownership may become an issue if the supplier's material waits for significant periods in the third-party facility.

In addition to simple storage, here are the most common third-party logistics services:

- Repacking into desired containers or quantities (if not practical at the supplier's)
- Consolidation and segregation of materials for delivery to specific docks or portions of a plant
- Sequencing and kitting of materials for delivery to assembly lines
- Assembling several parts or items for delivery to a consuming operation within the plant
- Metering of deliveries to avoid activity peaks and valleys at receiving docks

Before such services are retained, the industrial engineer may be called upon to justify them in terms of internal labor savings, space savings, and various forms of cost avoidance.

Planning Information

In order to plan physical systems for receiving, handling, and storing of incoming materials, the industrial engineer should understand the following aspects of ordering and scheduling for each major family or type of parts and, ultimately, for each item or part number if detailed plans are required.

- Consumption rate and pattern: average, maximum, and variability
- Supplier's replenishment lead time, from receipt of order or release to shipment
- Transit time—and variability—from supplier or logistics service company, if used
- Arrival times, if regularly scheduled: day(s) and hours or frequencies
- Operating times and calendars at supplier and customer locations, especially any extended shutdowns or holidays that might delay shipments or receipts
- Target or desired inventory levels, in days' supply or dollars
  - —Minimum safety stocks
  - —Average on hand
- Ordering patterns
  - —Fixed interval (e.g., daily or weekly)
  - —Preestablished reorder point (e.g., number of units or days' supply)
  - —As consumed (e.g., kanban signal or one-for-one)
  - —Variable, as determined by a plan or forecast of requirements
  - —As needed (e.g., ordered-to-order specials)
  - —Opportunistic (e.g., end of fiscal year or season, when manufacturers may offer an incentive for large or closeout orders)
- Order size and quantities
  - —Preestablished, fixed order quantity (e.g., number of units or containers)
  - —Variable quantity, in units or containers
  - —Rounded quantity to nearest standard container
- Container types and sizes
  - —Desired at point of use: returnable or one-way; dimensions, weight, handling equipment required, labeling, and identification
  - —Currently used or preferred by supplier

- Ownership of the inventory
  - —Consigned or owned; by customer or by supplier
  - —Responsibility for receiving, putaway and delivery to point of use

Scheduling and ordering information can be summarized on a form like that shown in Fig. 10.1.2. With this information in hand, the industrial engineer determines the capacities required to receive, handle, and store purchased parts and materials. In storage, provision must be made for the maximum inventory to be held. This is usually estimated as the minimum plus the typical or largest receipt. In reality, the maximum may exceed this estimate if consumption during the replenishment lead time is lower than expected. (See Fig. 10.1.3.)

If quantities are expressed in days' supply, the industrial engineer must be sure that calculations are made using the proper production rates or consumption volumes. Note that as production rates increase and decrease, the quantity represented by a day's supply also changes. If such changes are great enough, it may be necessary to review and modify lot sizes, run frequencies, container sizes, and packing quantities.

Container Planning

The industrial engineer can make a major contribution to efficiency by making sure that containers are appropriately designed and sized to accommodate the supplier, the carrier, the internal material handler, and the user or consumer of parts and materials. While we are primarily discussing inbound deliveries from suppliers, this contribution also applies to containers and packaging used for outbound shipment of finished goods.

As purchased parts flow from supplier to customer, the desired lot size changes based on the economics and practical limitations of production, transportation, and material handling. (See Fig. 10.1.4.) Good container planning recognizes and accommodates these changes with standard, modular sizes and designs that can be conveniently transported, handled, and stored. At the same time, the principal requirements of protecting and presenting the contents of the container must be maintained. To make sound container decisions, the industrial engineer will need to visualize and study the routes or paths of materials from their origins to their destinations. Particular attention should be paid to points of contact during filling, picking up, setting down, loading for transport and then unloading, and finally for emptying or removing the contents at point of use. Return, reuse, or disposal of the container may also be important. Figure 10.1.5 presents a comprehensive list of factors or considerations for container selection.

Some advocate using factors of 60 (60, 30, 20, 15, 12, 10, 6, 5, 4, 3, 2, 1) when establishing standard packaging and lot sizes, especially when modular totes or bins will be used. These factors typically provide sufficient range to decouple the standard pack from the customer consumption rate, yet still approximate it very closely with the replenishment process. Also, they lend themselves to a variety of container sizes. When kitting parts from several suppliers, it will help if the parts are received in common-factor quantities.

TRANSPORT LOAD PLANNING

Load planning balances the desire to fully utilize the cube of transport vehicles and containers against weight and stacking restrictions of the cargo or shipping containers. Heavy cargo may reach the maximum weight capacity of the vehicle or transport container before the cube is fully used. Conversely, bulky or lightweight shipments may "cube out" before reaching the weight capacity. Poor utilization and unnecessary transport costs may result from specification or selection of shipping containers or pallet and load dimensions without regard to their fit with transport container dimensions. In addition to compatibility with shipping containers

INVENTORY PLANNING INFORMATION

Company/Unit/Plant *Oil Products, Ltd.* Project *Finished Goods Storage*

By *LH* with *KH, RM, BA* Date *8/10* Sheet *1* of *1*

		Usage				Timing				Planned Inventory Levels					Containers	
Materials, Products, or Family of Products	No. of different items	Unit of Measure/ Issue/Consumption	Cost/Value per unit ($)	Usage per period (week)	Variability of usage	Production/Supplier Lead Time	Transit Lead Time	Reorder Point/Release Frequency	Shipment/Delivery Frequency	Reorder/Release Quantity	Shipment/Delivery Quantity	Minimum (Safety stock)	Maximum	Expected Average	Delivery Container (as received)	Units per Container
a	b	c	d	e	f	g	h	i	j	k	l	o	p	q	m	n
M1C08	*1*	*carton*	*72*	*940*	*Low*	*3d*	*1d*	*weekly*	*daily*	*940*	*192*	*188*	*380*	*284*	*pallet*	*48*
M3C04	*1*	*carton*	*72*	*760*	*Low*	*3d*	*1d*	*reorder at 760*	*as req'd*	*1248*	*1248*	*152*	*1400*	*776*	*pallet*	*48*
M1D08	*1*	*drum*	*450*	*110*	*Low*	*3d*	*1d*	*reorder at 110*	*as req'd*	*192*	*192*	*22*	*214*	*118*	*pallet*	*4*
M4C05	*1*	*carton*	*72*	*490*	*Mod*	*3d*	*1d*	*reorder at 539*	*as req'd*	*1008*	*1008*	*147*	*1155*	*651*	*pallet*	*48*
G2C09	*1*	*carton*	*108*	*270*	*Mod*	*3d*	*1d*	*reorder at 297*	*as req'd*	*864*	*864*	*81*	*945*	*513*	*pallet*	*36*
M3D04	*1*	*drum*	*450*	*60*	*Mod*	*3d*	*1d*	*reorder at 66*	*as req'd*	*140*	*140*	*18*	*158*	*88*	*pallet*	*4*
V5C10	*1*	*carton*	*90*	*270*	*Mod*	*3d*	*1d*	*reorder at 299*	*as req'd*	*684*	*684*	*81*	*765*	*423*	*pallet*	*36*
M4C06	*1*	*carton*	*450*	*50*	*Mod*	*3d*	*1d*	*reorder at 55*	*as req'd*	*144*	*144*	*15*	*159*	*87*	*pallet*	*48*
G2D09	*1*	*drum*	*675*	*27*	*Mod*	*3d*	*1d*	*reorder at 30*	*as req'd*	*112*	*112*	*8*	*120*	*64*	*pallet*	*4*
V4C03	*1*	*carton*	*90*	*185*	*Mod*	*3d*	*1d*	*reorder at 204*	*as req'd*	*576*	*576*	*56*	*632*	*344*	*pallet*	*36*
MC Family	*7*	*carton*	*72*	*805*	*Mod*	*9d*	*1d*	*2 weeks*	*2w*	*1610*	*1610*	*805*	*2415*	*1610*	*pallet*	*48*
MD Family	*3*	*drum*	*450*	*53*	*Mod*	*9d*	*1d*	*2 weeks*	*2w*	*106*	*106*	*53*	*159*	*106*	*pallet*	*48*
TC Family	*7*	*carton*	*72*	*613*	*Mod*	*9d*	*1d*	*2 weeks*	*2w*	*1226*	*1226*	*613*	*1839*	*1226*	*pallet*	*48*
VC Family	*3*	*carton*	*90*	*150*	*Mod*	*9d*	*1d*	*2 weeks*	*2w*	*300*	*300*	*150*	*450*	*300*	*pallet*	*36*
GC Family	*5*	*carton*	*108*	*158*	*Mod*	*9d*	*1d*	*4 weeks*	*4w*	*632*	*632*	*316*	*948*	*632*	*pallet*	*36*
GD Family	*5*	*drum*	*675*	*9*	*High*	*9d*	*1d*	*6 weeks*	*6w*	*54*	*54*	*36*	*90*	*63*	*pallet*	*4*
RD Family	*15*	*drum*	*675*	*23*	*High*	*7d*	*2d*	*8 weeks*	*8w*	*184*	*184*	*138*	*322*	*230*	*pallet*	*4*
RC Family	*22*	*carton*	*108*	*137*	*High*	*7d*	*2d*	*8 weeks*	*8w*	*1096*	*1096*	*822*	*1918*	*1370*	*pallet*	*48*
Cartons	*51*			*4828*							*Cartons*	*3,426*	*13,006*	*8,216*		
Drums	*26*			*282*							*Drums*	*275*	*1,063*	*669*		

FIGURE 10.1.2 Scheduling and ordering information.

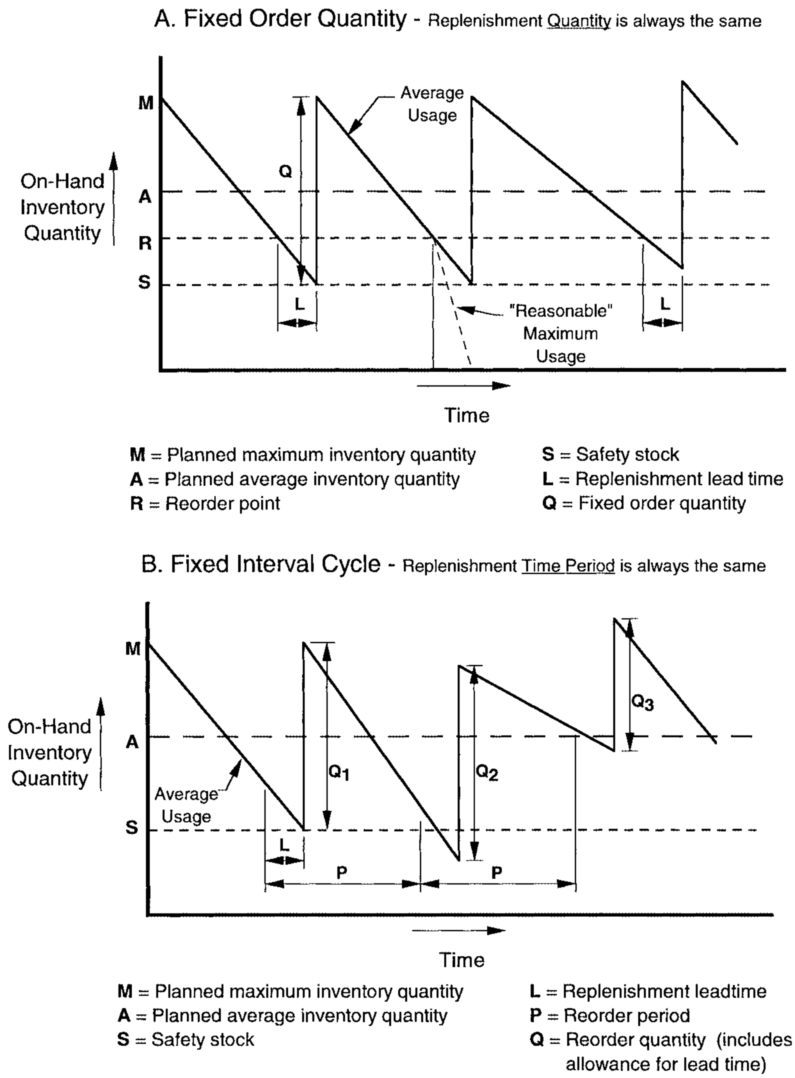


FIGURE 10.1.3 Theoretical inventory movement patterns.

and loads, the chosen transport container and vehicle must also be compatible with the loading and unloading equipment and facilities at each pickup point and destination.

Problems may be posed by diverse shipments of nonstandard items or special containers and fixtures. Here, the planner must consider loading and unloading sequences, potential physical interference of loads, their placement and weight distribution relative to vehicle axles and frames, and the potential for shifting in transit. In the absence of standard containers, these issues are common on pickup and delivery routes or milk runs.

When planning multistop routes, the time required to load or unload at each stop must be calculated with reasonable precision. Travel time to reach a stop and its variability must also be established. Transportation modeling and simulation software may be used for these pur-

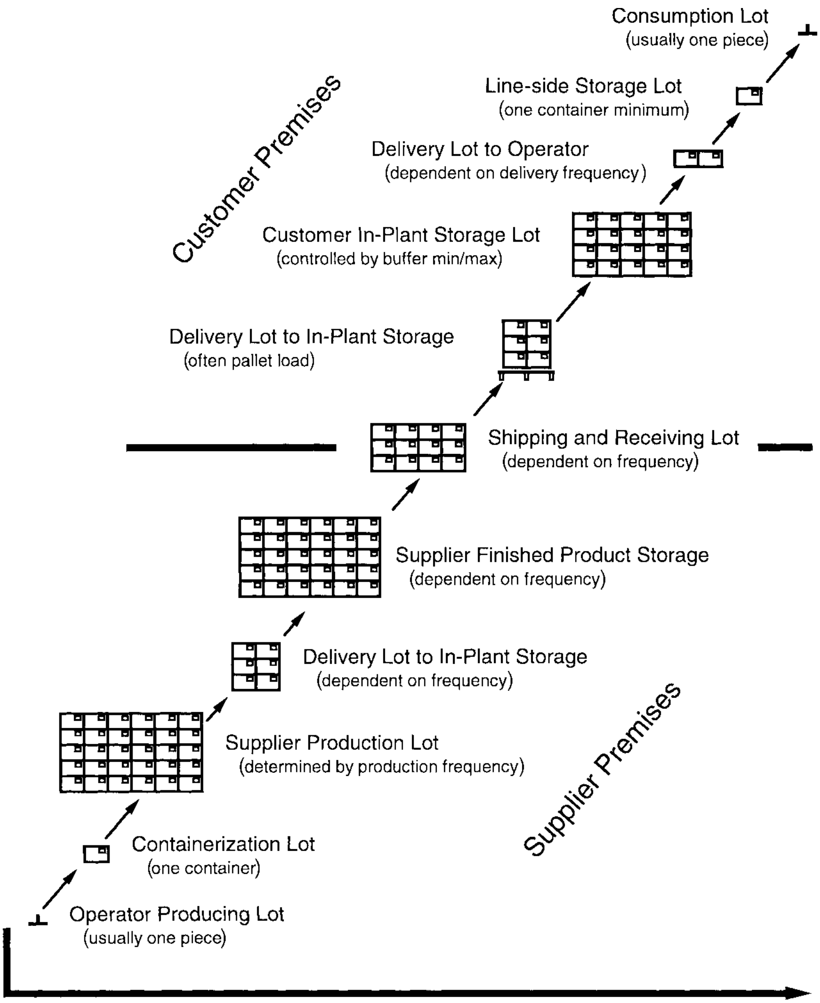

Consumption Lot
(usually one piece)
Line-side Storage Lot
(one container minimum)
Delivery Lot to Operator
(dependent on delivery frequency)
Customer Premises
Customer In-Plant Storage Lot
(controlled by buffer min/max)
Delivery Lot to In-Plant Storage
(often pallet load)
Shipping and Receiving Lot
(dependent on frequency)
Supplier Finished Product Storage
(dependent on frequency)
Delivery Lot to In-Plant Storage
(dependent on frequency)
Supplier Production Lot
(determined by production frequency)
Supplier Premises
Containerization Lot
(one container)
Operator Producing Lot
(usually one piece)

FIGURE 10.1.4 Material flow lot sizes.

poses. Once the total cost to serve a stop is known, the load planner can establish the minimum load volumes and inventory values that would justify regular pickups or deliveries. Locations below the minimum are typically served by special, as-needed transportation. Locations with heavy volume may be served with dedicated transportation to avoid "flooding" the route and crowding out other stops along the way.

Use of Third-Party Logistics

Often the goal is to unload shipments in a particular order or sequence. But it may be impractical to build this sequence as pickups are made. And the sequence may involve materials from more than one pickup route. In these situations, it may be cost-effective for a logistics service company to build the desired sequence at its facilities and then deliver the sequenced

P = Characteristics of contained product or parts

- What is the product or part size?
- What is the weight?
- What is the shape?
- What is the risk of damage to the product?
- Does it require aeration?
- Does it require protection from air or water?
- Does it require drainage?
- Does it require thermal insulation?
- Does it require electrostatic insulation?

Q = Quantity of contained product or parts

- What is the typical transport quantity?
- What is the maximum transport quantity?
- What is the consumption rate and quantity?

R = Conditions of the container's route(s), handling points, and storage

- How will the product or parts get into the container?
- Must part orientation be maintained?
- How will the container be handled (picked up and set down) at each handling point?
- How often will the container be handled?
- What is the maximum allowable loaded weight?
- How will the container be transported?
- Must the container fit into another container?
- Are there special environmental conditions (heat, humidity, corrosives, etc.)?
- How will the container be stored?
- How will the products or parts get out of the container?
- Must it stack?
- Must it nest?
- Must it be returnable?
- Must it be recyclable?

S = Supporting information

- Do industry standards apply?
- What is the container's cost?
- What type of labels or tags must the container support?

T = Time-related considerations

- What is the useful life of the container?
- Is the need for containers seasonal?
- How long will the contained items remain in use?

FIGURE 10.1.5 Container selection factors.

load to the plant or warehouse. This approach will, of course, be used if the service company has also been retained for the consolidation, kitting, or assembly services mentioned previously.

Often, carriers or logistics service companies will plan transport loads. Still, the industrial engineer needs to understand the thinking behind the loads and be sure that they provide the desired efficiency at receiving locations. The industrial engineer should also participate in decisions that may give carriers or service companies (or suppliers) the responsibility for material handling inside the plant or warehouse. The use of an outside party to load or unload or to deliver materials to storage or production will have some impact on internal human resources requirements and on the choice of handling and storage methods. Additional considerations include safety, insurance liability, work rules, and labor relations.

Pooled Pallets and Containers

In some industries it is common for shippers to use pallets or containers that belong to a party other than the shipper or receiver—commonly referred to as a *pool.* The container provider, or pool, receives a fee in return for providing a ready supply of containers. The container provider also arranges for tracking and recovering empties and performs any cleaning or repair that may be required. Use of pooled pallets and containers should relieve the shipper of the need to clean, handle, and store fresh empties and to dispose of those that are no longer usable. These arrangements also promote standardization of sizes and dimensions; however, they may favor full utilization of the transport vehicle and container over convenience and ease of handling at point of use or consumption.

MATERIAL HANDLING AND STORAGE ANALYSIS

Methods of transport *between* sites are typically determined by the transportation management or traffic function. The industrial engineer is typically responsible for methods of material handling *within* sites and facilities. Storage methods are also decided by the industrial engineer, and these must be compatible with the handling methods used to deliver or put away and to order pick or withdraw material from storage.

While the methods selected may vary for purchased materials, work in process, and finished goods, the decision-making considerations, analyses, and selection factors are generally common for all three types of inventory. For this reason, we will present a single discussion of material handling and storage analysis. For ease of understanding, we will look first at material handling and then at storage. In practice, the selection of handling and storing methods must be made concurrently.

Material Handling Methods

Methods determine how materials are moved between their origins and destinations. A material handling method consists of the following:

1. The *system* of which the move is a part
2. The *equipment* used to make the move
3. The *transport unit* or container being moved

Given the great variety of moves to be made in the typical industrial facility, it is no surprise that many different material handling methods are usually needed. In fact, the industrial engineer should guard against simplistic, overly standardized, or one-size-fits-all decisions and plans. To ensure that plans are practical and cost-effective, each move should be examined with respect to its most appropriate system, equipment, and transport unit. This analysis of internal moves should begin after basic decisions have been made on ordering and scheduling, use of logistics service providers, transportation planning, and containers. These decisions provide context and constraints on internal methods selection. In practice, there is always some overlapping give-and-take, as the preferred internal methods influence the external integration with transportation, service companies, suppliers, and customers.

Movement Systems. *System* refers to the way or pattern in which moves are tied together in geographical and physical terms. Systems can be direct or indirect. In a *direct* system, different materials move separately and directly from origin to destination, one move at a time, and usually on the shortest possible path—for example, a forklift moving a pallet loaded with a single part from one location to another or a dedicated conveyor connecting two operations.

In contrast, an *indirect* system moves materials to and from different areas together on the same (shared) equipment, usually along a predefined route having several potential stops. In this system, a given material may pass several stops or drop-offs before reaching its own destination. Think of a tractor or tug pulling several carts or wagonloads of multiple parts and items or a system of collecting conveyors feeding into a sortation system and shipping lanes.

The choice of movement system depends largely on the distance of the moves to be made and the rate or intensity of flow—that is, the quantity moved per period of time. When distance is short or moderate and the intensity of flow is high, the direct system is typically the most economical, especially if the materials are special in some way or the moves are urgent. When distance is moderate or long and the intensity is just moderate or low, indirect systems are better, since movement costs are spread across all of the materials being moved.

A special form of indirect system is the route-based replenishment of production floor stock, assembly lines, and forward picking or packaging lines in distribution centers. This type of indirect system operates between a receiving or central storage area, sometimes referred to as a *supermarket,* and various points of staging, local storage, or consumption on the floor of the plant or warehouse. Indirect replenishment systems can take one of three basic forms:

- *Decoupled pick and deliver.* A separate handler picks and builds the next load while the delivery person is in transit. Best when load building is faster than delivery and two or more delivery routes could be built by one material handler. Also favored when the longer replenishment time of combined pick and deliver would lead to larger inventories on the floor.
- *Combined pick and deliver.* The same material handler picks material from storage before beginning the route, then delivers picked material to designated points along the line. Best when the handler is assigned to the areas being served and not to a central handling or storage organization. Also when delivery frequency and inventory coverage is not critical (since the replenishment interval is longer).
- *Decoupled delivery and replenish.* An intermediate "drop zone" is used between the origin in receiving or central storage and the final points of use on the floor or line. One handler brings material to the drop zone. A second, local handler completes the move to point of use. This method adds an extra move, but may be desirable in very crowded conditions with dead-ended delivery aisles and/or lack of vehicle access at final delivery points.

Handling Equipment. Industrial trucks and conveyors are the most common types of material handling equipment in manufacturing plants and distribution facilities. Storage-and-retrieval cranes may also be used in high-bay storage situations. Each type of equipment is available in many forms and specialized configurations (too numerous to discuss in a short chapter such as this). As a general rule, the physical characteristics of the materials being moved are the first, and often most important, consideration in selecting the right equipment. These characteristics include size, weight, shape, risk of damage, and condition of the material or its container. Also critical is the physical condition and situation of the route, including the pickup and set-down points. Highly restricted situations may dictate a certain type of equipment.

In facilities larger than 30,000 square feet or 3000 square meters, the distance of the moves to be made and their flow rates or intensities are important factors when selecting handling equipment. (In smaller facilities, all moves are relatively short, so distance is not a discriminating factor.) Both distance and intensity have major impact on movement costs. Distance determines whether equipment should be selected for

- *Handling*—quick and easy (inexpensive) to load and unload, but poorly suited (costly) for long hauls, usually because of slow travel speed and/or small load capacity.
- *Travel*—designed for inexpensive long hauls, but typically more costly to load and unload, usually because of the larger load being transported.

This distinction is important, because on short routes, most of the move cost is in loading and unloading (pickup and set-down). Using travel-oriented equipment will likely incur unnecessary cost. The converse is true if handling equipment is used for travel on long routes.

Intensity of flow determines whether equipment should be simple or complex.

- Simple equipment is typically inexpensive to buy and own, but it incurs a high variable (direct) cost to operate, generally because of labor.
- Complex equipment is expensive to buy and own, but has low variable (direct operating) costs, generally because it is mechanized or automated and thus requires less labor.

Integrating these considerations gives four general classes of material handling equipment and associated suitabilities:

- *Simple handling.* Use for short distances and low intensities of flow.
- *Complex handling.* Use for short distances and high intensities of flow.
- *Simple travel.* Use for long distances and low intensities.
- *Complex travel.* Use for long distances and high intensities.

These classes and their relationship to distance and flow intensity are illustrated in Fig. 10.1.6 for several industrial vehicles. Complex travel equipment is generally the most costly choice, especially when it must be dedicated to direct movement of one or a few high-intensity material flows. Before recommending such equipment, the industrial engineer should review the layout to see if long routes can be shortened, thus reducing material handling costs. If not, the transport unit should be reviewed to see if larger loads could be moved less often. This will reduce the cost of high-intensity, long-distance routes.

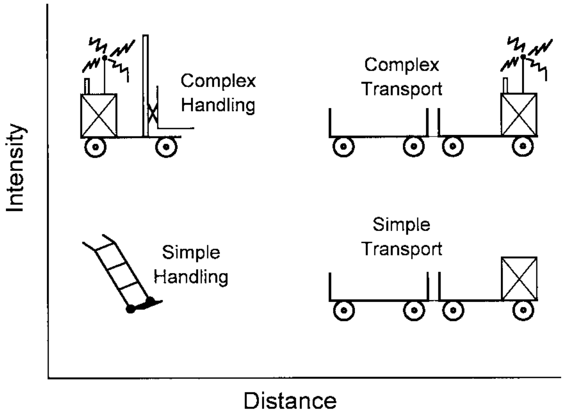


FIGURE 10.1.6 Preferred type of vehicle depends on distance and intensity.

Transport Units. The term *transport unit* describes the form or condition of material while it is being moved. The basic conditions are in bulk, as individual pieces, or in some kind of container.

If the material is suitable and the quantities are high, then bulk handling may be best, using belt conveyors, chutes, pipes, or pneumatic tubes.

Moving individual pieces is often best for very large, awkward, and/or easily damaged items that can be easily grabbed and supported. At the other extreme, it often makes sense to pass individual small parts or items from one operation to the next. Of course, the operations must be balanced to avoid buildup of loose items between operations. And if the movement is by hand, the operations must be within arm's reach or very close to one another. Such single-piece or one-piece flow avoids the cost of loading, unloading, and moving a container. Space may be saved, delays reduced, and investment in handling equipment may be avoided. Even when there is significant distance between operations, high-intensity moves of small parts in a plant or cartons in a warehouse may still favor individual-piece flow, since a near-bulk-handling stream of material can be achieved.

Most moves call for some form of container or support. Individual items are grouped or batched to form one unit by intelligent use of pallets, tubs, baskets, cartons, crates, drums, and the like. Of course, these unitized or unit loads are bigger and heavier and often require handling methods of greater capacity. A unit load protects items during movement and spreads the cost of the move over a larger transport quantity. This frequently reduces the move cost per piece. Containers also provide built-in buffers between operations and a convenient physical means of inventory control. In addition to pallets, skids, totes, boxes, and baskets, unit loads can also be achieved through nesting and banding or bundling of individual items. Containers should be selected using the criteria listed earlier in Fig. 10.1.5 and considering the external lot-sizing issues depicted earlier in Fig. 10.1.4.

In addition to selecting the type and size of container, the industrial engineer must also specify the quantity of materials or parts to be contained. Large containers and quantities tend to lower overall material handling costs, since fewer moves are required for a given volume of material. However, this potential for reduced movement cost must be balanced against the possible operational benefits of smaller quantities and containers. These include space savings at points of loading and use and reduced inventory in transit. The general trend in manufacturing is toward more-continuous flows of material, even if they require more frequent moves of smaller containers and quantities.

Standardization and consistency in container sizes, shapes, and designs lead to real savings at pickup and set-down points. This also neutralizes the variety of items to be moved and may reduce the need for different kinds of handling equipment in any given facility.

Storage Analysis and Equipment

Storage equipment is used to hold material between moves and operations. The choice of storage equipment must be compatible with

- The container or physical form of the material to be stored.
- The handling equipment used to deliver and put away into storage.
- The handling equipment used to withdraw and take material away.

Storage equipment can be simple and static, such as the floor itself, or a simple shelf or rack. At the other extreme, storage equipment can be complex and dynamic, such as an automated storage and retrieval system or a mechanized carousel. Between these extremes, the cost of providing a given amount of storage capacity can easily vary by an order of magnitude, from a few dollars to a few hundred dollars. The most cost-effective storage equipment is largely determined through analysis of the material *flow* to and from storage and the *level* or quantity of material to be held.

Each time that material is stored, a *handling cost* is incurred to place the material into storage and to remove it later when needed. The flow or rate at which the material is moved into and out of storage determines this handling cost. *Holding costs* are also incurred. These are determined by the level or quantity of material being held, the cost of carrying the inventory, and the duration of the hold. Carrying cost is an estimated value set by finance or accounting. It typically reflects the interest on money invested in the material and storage equipment, obsolescence, taxes, insurance, and the occupancy cost of storage space (rent or ownership, utilities, services, etc.). All but the cost of space are beyond the control or influence of the indus-

INDUSTRIAL ENGINEERING SUPPORT FOR MATERIALS MANAGEMENT

trial engineer and the storage equipment decision. Selection of higher-density equipment will reduce space costs.

Applying the concepts of handling and holding costs results in four general classes of storage equipment and associated suitabilities:

- *Simple storage and picking.* Easy to access for putaway and picking or retrieval. May require more space per unit, usually because of larger aisle allowances and less use of vertical space. Typical examples: bin shelving, decked pallet rack, selective pallet rack. Use for moderate- to low-flow materials having moderate to low levels of inventory on hand.
- *Complex staging and picking.* For short-term accumulation, presentation, and picking or for temporary set-down of high-flow material. Live or mechanized for velocity. Typical examples: flow rack, floor-staging conveyors or shuttle systems; horizontal carousels and miniload storage-and-retrieval machines when used to stage or accumulate. Inherently more complex than simple methods. Use for highest-flow materials with relatively low storage levels.
- *High-density storage.* Designed to minimize space per storage position, typically by reducing aisle allowances and increasing storage heights. Usually slower and therefore more costly to access for putaway and retrieval. Typical examples: bulk floor stacking, drive-in rack, and push-back rack. Use for low-flow material with high levels of inventory on hand.
- *High-density storage and picking.* Minimizes space per position while still providing relatively fast access for putaway and retrieval. Uses live storage and often-complex mechanization or automation. Typical examples: deep-lane pallet flow rack and automated storage-and-retrieval systems. Use for high-flow materials with high levels on hand.

Particular instances of these four classes are pictured in Fig. 10.1.7 for large, unitized loads and in Fig. 10.1.8 for cases, cartons, and totes. Flow and level are shown on a relative scale, from low to high. In practical application, the industrial engineer must scale these conceptual charts to the physical realities and economics of each situation. Given the variety of materials flowing through the typical industrial facility and their associated flow rates and storage levels, several and possibly many different types of storage equipment will be needed.

Before finalizing the selection of storage equipment, its compatibility with material handling must be checked and understood. The relationships between common types of handling and storage equipment are shown in Figs. 10.1.9 and 10.1.10.

An integrated guide to selecting both handling and storing methods is presented in Fig. 10.1.11. This guide culminates in an evaluation of both costs and intangibles. Costs should include the investment and operating costs associated with each alternative. Intangibles should include factors such as the following:

- Fit with and ability to serve processing operations
- Versatility and adaptability
- Flexibility and expandability
- Space utilization
- Safety
- Housekeeping
- Ease of supervision and control
- Ease of installation
- Tie-in or fit with procedures and information systems
- Maintainability, reliability, and service of equipment
- Operator acceptance and personnel issues

Often, the costs of different proposals will fall within a fairly narrow range, and intangible factors will become the primary basis for selecting handling and storing methods.

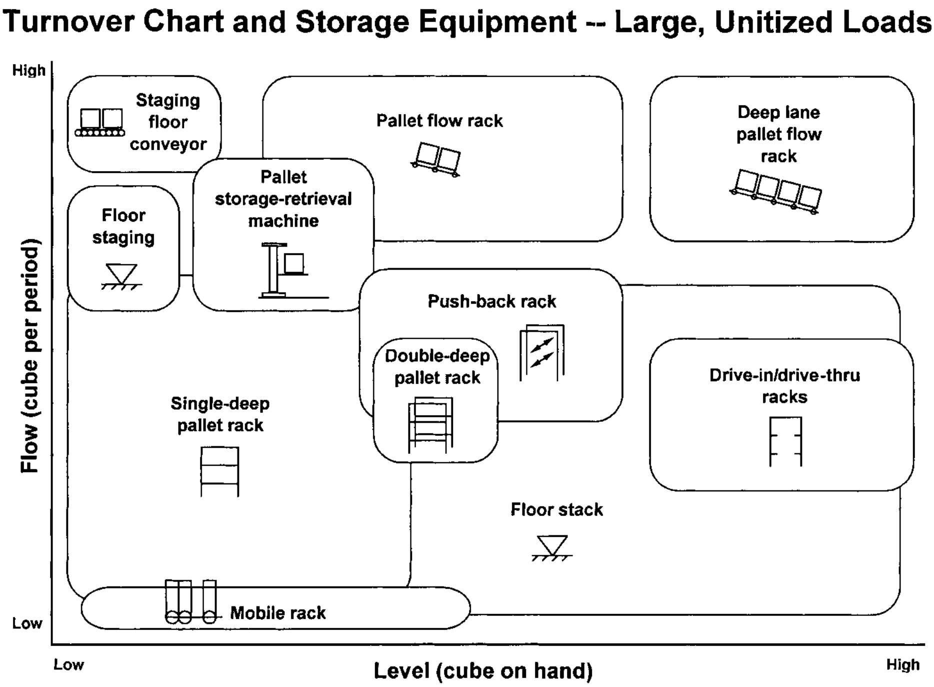

Turnover Chart and Storage Equipment -- Large, Unitized Loads
High
Staging floor conveyor
Pallet flow rack
Deep lane pallet flow rack
Pallet storage-retrieval machine
Floor staging
Push-back rack
Double-deep pallet rack
Drive-in/drive-thru racks
Single-deep pallet rack
Floor stack
Mobile rack
Low
Flow (cube per period)
Low
Level (cube on hand)
High

FIGURE 10.1.7 Preferred type of unit-load storage equipment depends on flow and level.

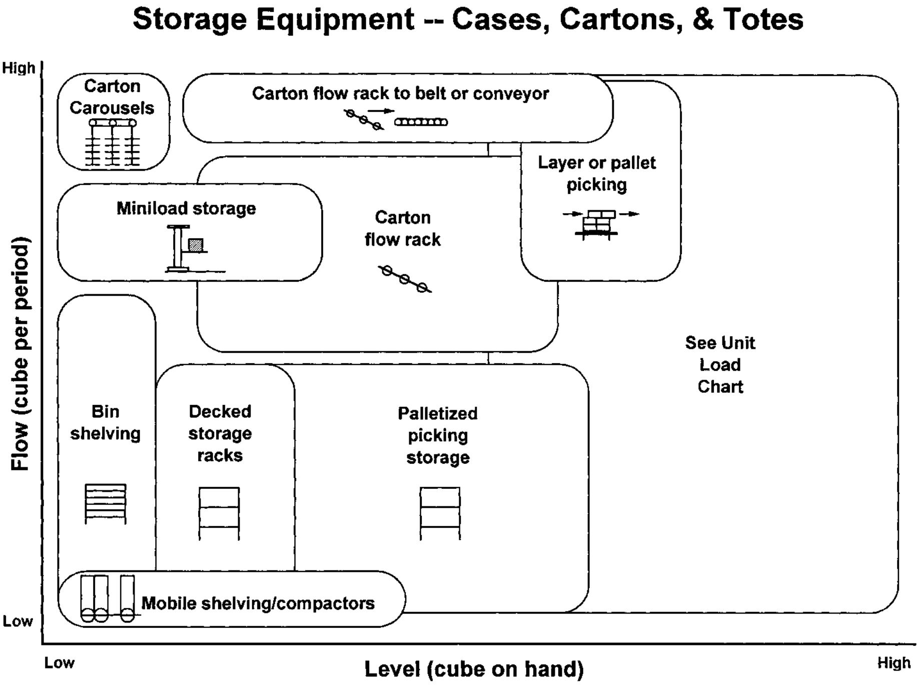
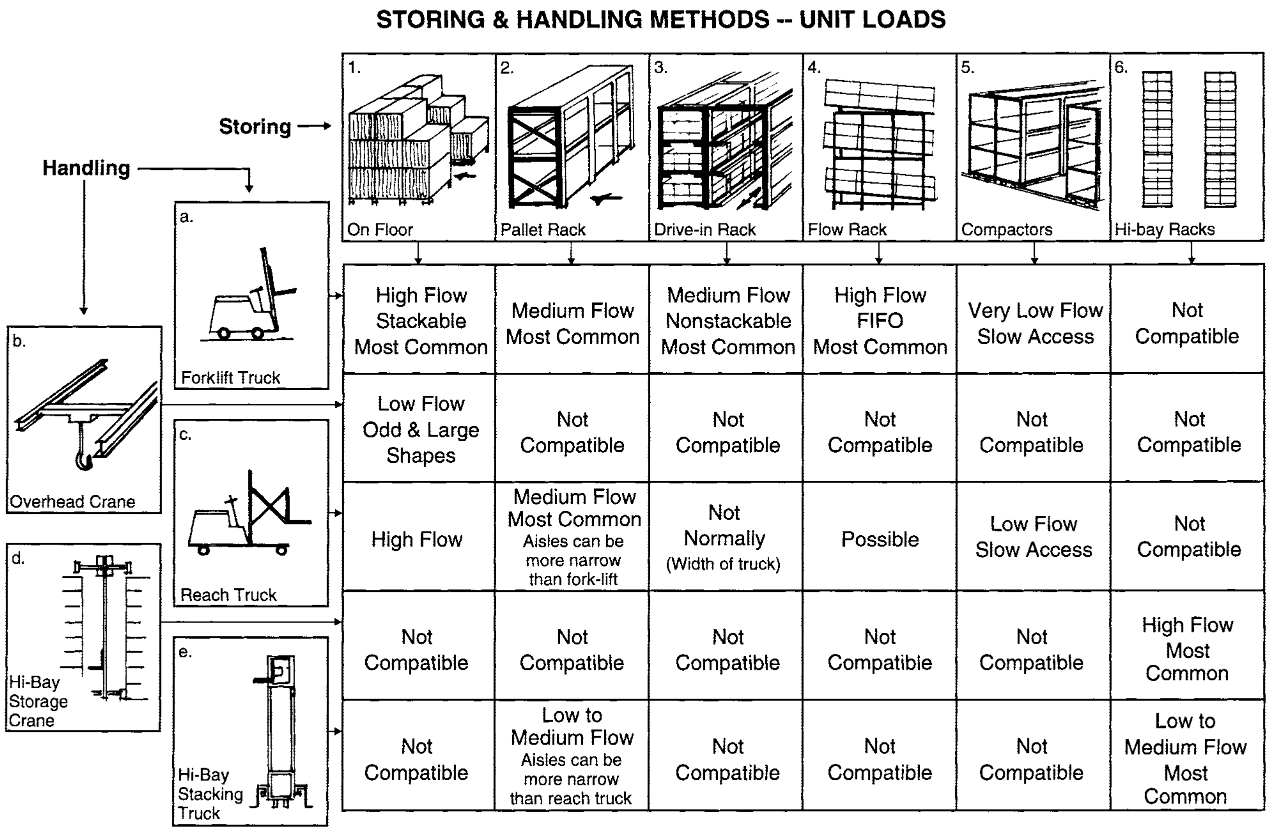
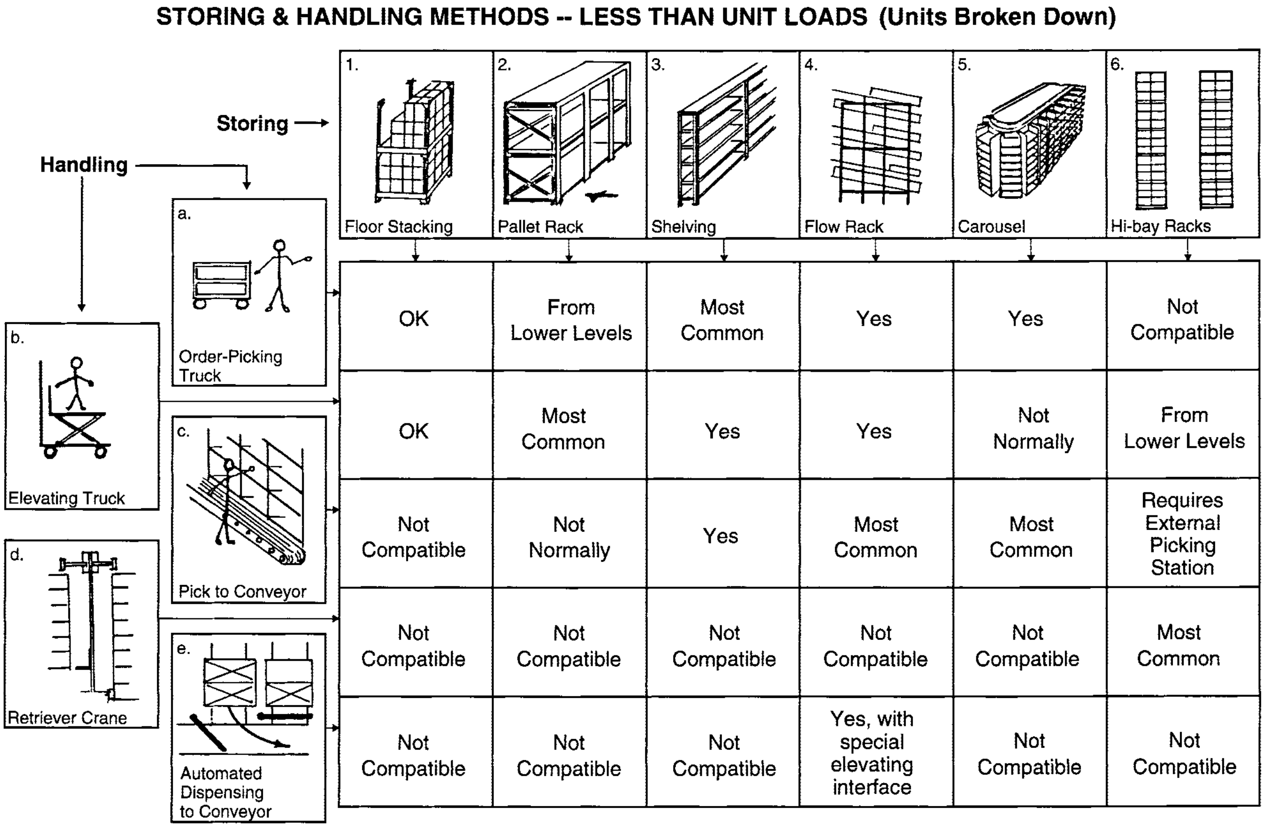

Storage Equipment -- Cases, Cartons, & Totes
High
Carton Carousels
Carton flow rack to belt or conveyor
Layer or pallet picking
Miniload storage
Carton flow rack
See Unit Load Chart
Bin shelving
Decked storage racks
Palletized picking storage
Mobile shelving/compactors
Low
Flow (cube per period)
Low
Level (cube on hand)
High

FIGURE 10.1.8 Preferred type of carton, case, and tote storage equipment depends on flow and level.


STORING & HANDLING METHODS -- UNIT LOADS
Storing
Handling
1. On Floor
2. Pallet Rack
3. Drive-in Rack
4. Flow Rack
5. Compactors
6. Hi-bay Racks
a. Forklift Truck
b. Overhead Crane
c. Reach Truck
d. Hi-Bay Storage Crane
e. Hi-Bay Stacking Truck

Handling \ Storing	1. On Floor	2. Pallet Rack	3. Drive-in Rack	4. Flow Rack	5. Compactors	6. Hi-bay Racks
a. Forklift Truck	High Flow Stackable Most Common	Medium Flow Most Common	Medium Flow Nonstackable Most Common	High Flow FIFO Most Common	Very Low Flow Slow Access	Not Compatible
b. Overhead Crane	Low Flow Odd & Large Shapes	Not Compatible	Not Compatible	Not Compatible	Not Compatible	Not Compatible
c. Reach Truck	High Flow	Medium Flow Most Common Aisles can be more narrow than fork-lift	Not Normally (Width of truck)	Possible	Low Flow Slow Access	Not Compatible
d. Hi-Bay Storage Crane	Not Compatible	Not Compatible	Not Compatible	Not Compatible	Not Compatible	High Flow Most Common
e. Hi-Bay Stacking Truck	Not Compatible	Low to Medium Flow Aisles can be more narrow than reach truck	Not Compatible	Not Compatible	Not Compatible	Low to Medium Flow Most Common

FIGURE 10.1.9 Compatibility of unit-load handling and storage equipment.


STORING & HANDLING METHODS -- LESS THAN UNIT LOADS (Units Broken Down)
Storing
Handling
1. Floor Stacking
2. Pallet Rack
3. Shelving
4. Flow Rack
5. Carousel
6. Hi-bay Racks
a. Order-Picking Truck
b. Elevating Truck
c. Pick to Conveyor
d. Retriever Crane
e. Automated Dispensing to Conveyor

Handling	1. Floor Stacking	2. Pallet Rack	3. Shelving	4. Flow Rack	5. Carousel	6. Hi-bay Racks
a. Order-Picking Truck	OK	From Lower Levels	Most Common	Yes	Yes	Not Compatible
b. Elevating Truck	OK	Most Common	Yes	Yes	Not Normally	From Lower Levels
c. Pick to Conveyor	Not Compatible	Not Normally	Yes	Most Common	Most Common	Requires External Picking Station
d. Retriever Crane	Not Compatible	Not Compatible	Not Compatible	Not Compatible	Not Compatible	Most Common
e. Automated Dispensing to Conveyor	Not Compatible	Not Compatible	Not Compatible	Yes, with special elevating interface	Not Compatible	Not Compatible

FIGURE 10.1.10 Compatibility of less-than-unit-load handling and storage equipment.

INDUSTRIAL ENGINEERING SUPPORT FOR MATERIALS MANAGEMENT

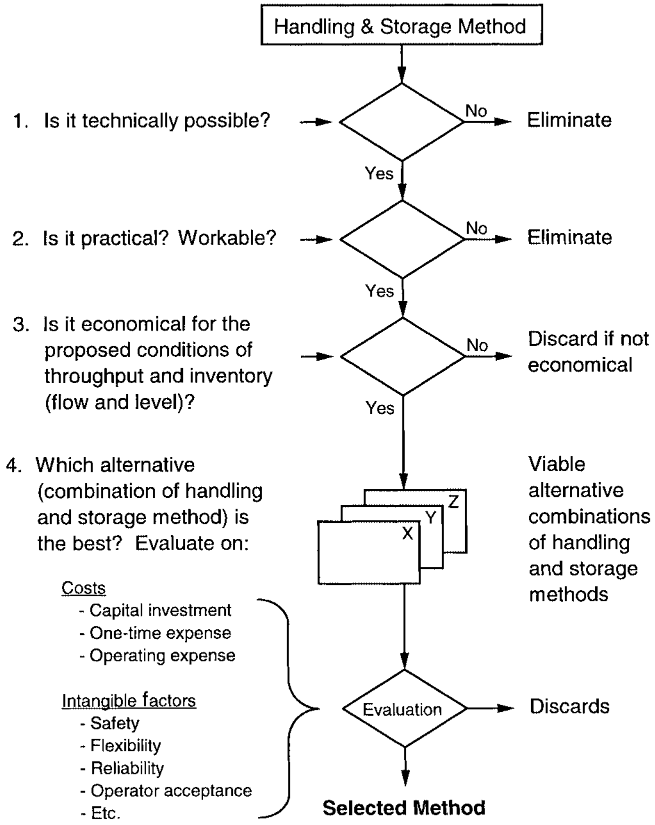

Handling & Storage Method
1. Is it technically possible?
No
Eliminate
Yes
2. Is it practical? Workable?
No
Eliminate
Yes
3. Is it economical for the proposed conditions of throughput and inventory (flow and level)?
No
Discard if not economical
Yes
4. Which alternative (combination of handling and storage method) is the best? Evaluate on:
Z
Y
X
Viable alternative combinations of handling and storage methods
Costs
- Capital investment
- One-time expense
- Operating expense
Intangible factors
- Safety
- Flexibility
- Reliability
- Operator acceptance
- Etc.
Evaluation
Discards
Selected Method

FIGURE 10.1.11 Selection procedure for handling and storage methods.

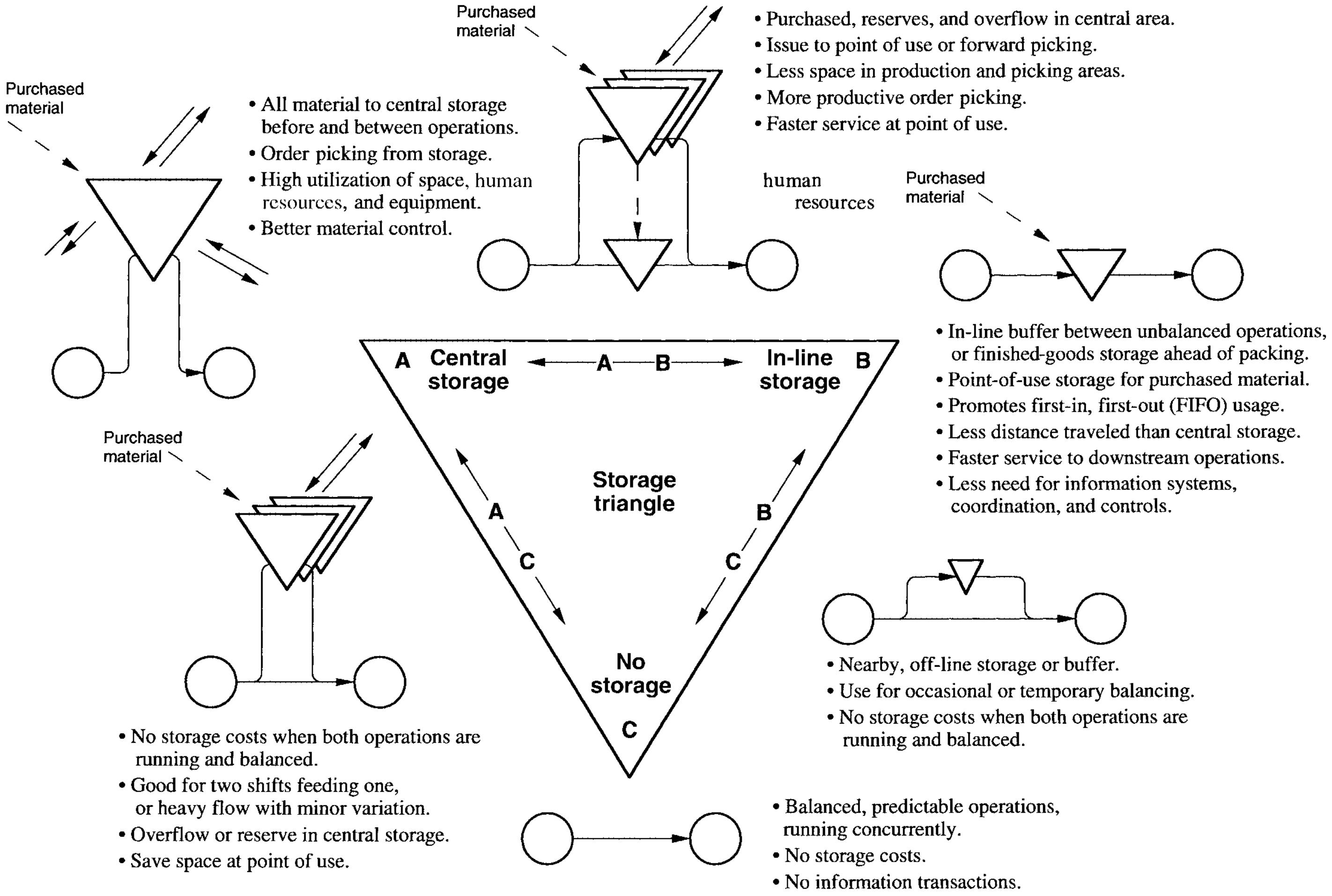
Location of Storage Areas

In addition to determining the types and amounts of storage equipment, the industrial engineer must also choose where to locate storage areas relative to the processing operations being served. In their pure forms, the three classical choices are as follows:

1. Central storage
2. In-line storage
3. No storage

These choices and their intermediate or hybrid variations are illustrated in Fig. 10.1.12. We will discuss them here as they apply to local layout decisions within a single facility. However, the choices are the same when deciding how and where to locate storage facilities between two producing operations in a supply chain.

Central Storage and Supermarkets. With the central approach, storage is consolidated into one or a few large areas. These receive, store, and issue materials to a variety of downstream operations, possibly including local and point-of-use storage or staging. This approach generally provides a high level of inventory control. Centralization often conserves valuable floor


Purchased material
Purchased material
Purchased material
Purchased material
human resources
A Central storage
In-line storage B
A
B
Storage triangle
A
C
B
C
No storage
C

- All material to central storage before and between operations.
- Order picking from storage.
- High utilization of space, human resources, and equipment.
- Better material control.

- Purchased, reserves, and overflow in central area.
- Issue to point of use or forward picking.
- Less space in production and picking areas.
- More productive order picking.
- Faster service at point of use.

- In-line buffer between unbalanced operations, or finished-goods storage ahead of packing.
- Point-of-use storage for purchased material.
- Promotes first-in, first-out (FIFO) usage.
- Less distance traveled than central storage.
- Faster service to downstream operations.
- Less need for information systems, coordination, and controls.

- Nearby, off-line storage or buffer.
- Use for occasional or temporary balancing.
- No storage costs when both operations are running and balanced.

- No storage costs when both operations are running and balanced.
- Good for two shifts feeding one, or heavy flow with minor variation.
- Overflow or reserve in central storage.
- Save space at point of use.

- Balanced, predictable operations, running concurrently.
- No storage costs.
- No information transactions.

FIGURE 10.1.12 Classical storage locations in relation to processing operations and movement.

space in production, makes better use of vertical space, and more efficient use of storage and handling labor. Often, the larger, consolidated storage operation will achieve flows and levels that justify more-complex and high-density equipment. A common example is the use of high-bay, automated storage-and-retrieval systems (AS/RS). Placed adjacent to receiving, the AS/RS is used to dispense stored or reserve material to production or to forward picking operations in distribution.

Some degree of central storage may be required if the material being held is consigned by outside suppliers. This may be the only safe or practical way to provide periodic access for inventory control and auditing. The issue from central storage into production may also serve as a convenient transaction point for paying the supplier and taking ownership of the material.

Central storage provides a convenient point to remove and dispose of packaging and dunnage, and it may be required if incoming material must be repacked into smaller containers, kitted, or otherwise prepared before delivery to points of use.

The most common problem with central storage is slow response time to requesting operations. Slowness may result from several underlying causes, which often include the following:

- Size. The central area becomes so large or remote from production that retrieval and delivery are slow. Travel times are high to requesting operations.
- Overly mechanized or automated and high-density equipment—typically slower to operate and subject to bottlenecks malfunctions, or downtime.
- Mismatched or poorly selected methods and equipment (relative to flows and demand).
- Administrative and information system delays.
- Understaffing.
- Focus on internal performance (e.g., productivity) at the expense of quick delivery.

When these problems are present, the downstream operations usually cope by making earlier requests and building up their own local buffers or decentralized storage in order to avoid delays, lost production, and idle time waiting for materials. If these actions are creating extra handling and inventory, the industrial engineer should consider the use of in-line and point-of-use storage.

In-Line and Point-of-Use Storage. In-line and point-of-use storage is decentralized and placed along the flow paths between processing operations. This minimizes distances and avoids travel to a remote central store. And by locating storage close to consuming operations, material can usually be placed under local, even visual, control and issued very quickly or at will, without reliance on a support function and without the need for costly information systems. For these reasons, in-line storage is favored for work-in-process and buffer stocks, especially in high-volume and cellular manufacturing and assembly. The amount required will be determined by several factors, including the balance or imbalance of production lot sizes at successive operations, run frequencies and scheduling practices, and container sizes and capacities. The distances between operations and the time required to move materials between them are also important.

Point-of-use storage generally refers to final, line-side or workplace storage or staging locations. From these, parts or materials are presented to a worker or processing operation. Point of use also describes the practice of delivering parts or materials directly from receiving to local storage within a processing department or operation. Often, the materials being delivered are considered to be *floor stock* or *free-issue*—meaning that they are no longer visible to the inventory control system. In this "uncontrolled" status, they can be handled in the same way as in-line storage. Issues, movement, and consumption can occur at the discretion of the local processing operation. Periodic replenishment may be made by a central function or even by an outside supplier or logistics service company.

When planning for in-line and point-of-use storage, the space available along the route and at points of use often governs the amount of storage provided and the type of equipment to be used. The amount of storage *desired* typically reflects the overall velocity or production rate through the facility and target inventory levels. Desired levels are generally expressed in minutes or hours of coverage, although days or even weeks may be appropriate in some industries and situations. But beware of preestablished management or inventory goals. The actual amounts of storage provided should be carefully calculated to consider the usage rate of each part, its replenishment lead time, and its variability.

Equipment selection for in-line and point-of-use storage follows the same principles outlined previously. If the flow is to high-volume, repetitive manufacturing and assembly, then live, mechanized equipment may be appropriate. If large volumes of material must be stored, this may justify high-density equipment, use of overhead space, and complex conveyorized or automated delivery.

If the flow and storage level are low and the pace of production is slow, then simpler, low-density equipment is more appropriate—shelving, decked racks, or even the floor itself. If floor space is very scarce and valuable or tight physical control is required, then expensive, high-density devices such as vertical carousels may be necessary.

Continuous Flow without Storage. The ideal and lowest-cost situation is to have a continuous flow of material with no storage at all. When material flows directly without being held between operations, there are no handling costs into and out of storage. And, of course, there are no costs associated with holding inventory. However, to achieve continuous flow requires that successive operations be concurrently available and synchronized to a common processing rate. In manufacturing, such operations are rarely achieved without the process and methods improvements discussed next.

In practice, some form of staging—temporary set-down or short-duration queue—is almost always required to compensate for variability in the operations or transfer time, for independent scheduling decisions and differences in processing hours or shifts, for downtime, and for mismatched lot sizes. Staging may consist of a few containers or individual pieces held directly on the floor, on a shelf or work surface, on a cart, or on a connecting conveyance (slide, chute, roller, skate wheel, etc.).

PROCESS AND METHODS IMPROVEMENT

Processing methods and equipment influence batch or lot sizes, run frequencies, and scheduling practices. These in turn influence the sizes of containers and loads and the frequency of their handling, transport, and storage. Container and load sizes and their movement frequencies determine storage locations and the methods for handling and storing materials. The methods chosen drive personnel requirements and productivity.

Often, by changing the processing methods and equipment, the industrial engineer can simplify or reduce the cost of handling and storage. Rarely are such changes undertaken for this purpose alone. But if changes are being considered to reduce costs, increase capacity, or improve quality and yields, they should also be examined for the opportunity to improve or reduce handling and storage. The industrial engineer should always explore these potential improvements first, before deciding on storage and handling methods and equipment.

Two types of process and methods improvement are universally valuable in materials management work: (1) setup reduction and (2) use of manufacturing cells or focused operations and teams.

Setup Reduction

Setup reduction lowers the cost and time required to make production changeovers. The time saved can be used to run more product or to change more frequently from one item to the

INDUSTRIAL ENGINEERING SUPPORT FOR MATERIALS MANAGEMENT

next. Thus, runs can be shorter and more frequent and more closely coupled to downstream demand. Lot sizes and containers can be smaller. The overall flow of material may be smoother, reducing costly peaks or surges that must be provided for by the material handling methods. For these reasons, the industrial engineer should carefully review opportunities for setup reduction, starting upstream with suppliers' operations and moving downstream through every point at which changeovers must occur. Specific improvements should be pursued with a cross-functional team, representing all of the jobs that participate in the target setup or changeover. Once the team is assembled, the following steps should be taken:

- *Videotape the setup.* Carefully videotape all steps from operation shutdown through full-speed production of the next lot or item. Review the videotape with the team and record the time required for each step or task.
- *Distinguish between internal and external setup steps or tasks.** Internal setup steps are those that can be accomplished only while the operation is stopped. External setup tasks are those that can take place while the operation is running.
- *Analyze the internal tasks and convert them to external.* This will allow additional setup work to be completed before shutdown, thus reducing the overall shutdown time.
- *Streamline both internal and external tasks.* Challenge the need for each task. Look for ways to simplify and reduce the time required.

Manufacturing Cells and Teams

Work cells or manufacturing cells dedicate equipment and personnel to one or a limited set of parts or products. Cells place operations very close together, often making it possible to flow individual pieces from one operation to the next. This typically has a dramatic impact on and may even eliminate the need for work in process. And, where final production or assembly cells can be coupled to customer demand or sales, finished goods may also be eliminated. The potential of cells is too great to ignore or overlook when planning for materials management systems. Beginning again with upstream suppliers, the industrial engineer should make sure that opportunities for cells are fully exploited at every step, through final assembly.

In distribution and warehousing, the use of focused teams may accomplish some of the benefits that cells provide in manufacturing. By giving teams end-to-end physical responsibility for a subset of materials, receipts, or orders, it is often possible to eliminate delays, setdowns, extra handlings, inspections, and order assembly.

WORK MEASUREMENT

Calculation of work content and comparison of labor costs are required when choosing the best handling and storage methods. The ability to measure work and the performance of physical operations are also essential when defining the jobs or positions that will be required. Observational time study, work sampling, and the application of predetermined time standards are valuable skills. Simulation may also be useful in estimating the performance of complex mechanized and automated systems. In support of materials management, the industrial engineer may apply these skills to develop the following standards and measures:

- Loading and unloading times for various types of loads, containers, and vehicles
- Delivery and putaway times for various types of handling and storing equipment

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* In this context, internal and external refer to setup tasks, not to elements of the processing operation itself.

- Travel times for various types of equipment and route conditions
- Pickup and set-down times and allowances for various types of physical handling and situations
- Manual handling times (pickup, set-down, turn, or reorient) at workplaces and storage positions
- Order picking and bin replenishment times for various types of containers, handling, and storage equipment
- Stop times in indirect replenishment systems
- Document processing times (obtaining, reading, writing, filing)
- Information systems transaction times for key entry, scanning, and display
- Allowances for personal fatigue and delay, time of day, peak conditions, and so forth

In addition to measuring labor and recurring tasks, industrial engineers are often asked to measure and report on the overall performance of the total system and facilities. Typical measures of interest in materials management include the following:

- Order-fulfillment time, from order acceptance or release to shipment
- Labor cost or person-hours per unit handled or stored
- Floor space employed per unit handled or stored
- Utilization of handling equipment (e.g., percent empty, percent idle, percent available)
- Utilization of storage equipment (e.g., percent of positions, percent of cube within positions)
- Utilization of docks
- Aggregate activity levels per period and time of day (e.g., receipts, orders, putaways, moves, picks, shipments)
- Inventory levels and turnover

INFORMATION SYSTEMS

Information systems are central to materials management. They have been used for many years to plan, schedule, order, release, and track materials. Increasingly, they are also being used to direct and control the physical movement and processing of materials. In factories, manufacturing execution systems (MES) may be used to direct production and material handling. In distribution, warehouse management systems (WMS) are commonly used to direct receiving, putaway, picking, packing, and shipping. Both types of systems—MES and WMS—require accurate, often real-time data on material and production status.

The industrial engineer's primary role in the support of these systems is the design and implementation of cost-effective and reliable methods for data acquisition. When information systems provide new capabilities, the IE is also responsible for evaluating their impact on job design, on labor requirements, and on handling and storage methods. Both of these roles require thorough understanding of the production and distribution processes themselves, along with knowledge of data acquisition technologies.

Common Automatic Identification Technologies

In materials management, data acquisition is generally synonymous with automatic identification. Speed and accuracy of data entry, coupled with relatively low equipment cost, make this technology almost universal in newly implemented systems. In manufacturing and distribution, the most common types of automatic identification include the following:

- Linear bar code labels
- Two-dimensional bar code labels
- Radio-frequency identification

Linear bar coding is most common. It employs printing and scanning equipment that is readily available, reliable, and relatively inexpensive. Linear bar coding is limited by the need for line-of-sight access when scanning and by the relatively small amount of information that can be contained in the spaces available for labels. Two-dimensional bar coding also requires line-of-sight access but can encode far more information. For example, in bill of lading (BOL) applications, linear bar codes are typically used only for key data elements such as the shipper number and BOL number. In contrast, two-dimensional bar codes can encode all of the information contained in the BOL, making this type of technology more desirable when significant amounts of information must be carried and read from a label.

Radio-frequency identification (RF/ID) employs electronic memory and a passive transponder on a tag or chip that is affixed to a product or container. A reading device emits radio waves that excite the transponder tag and enable data acquisition. RF/ID's primary advantage is that it does not require line of sight. However, the technology is not as mature as bar coding and is still more expensive.

Selecting Data Acquisition Points and Methods

Selecting points for data acquisition begins with a detailed list of the data elements required. Next, the industrial engineer should make a flowchart of the activities and processes involved. This flowchart can then be used to identify and select those tasks or points in the process that are best suited for capturing the required data. Most often, these will include material pickups and set-downs, putaway and picking from storage equipment, and mechanized transport paths such as conveyors. Common types of data acquisition equipment are as follows:

- Handheld scanners and terminals
- Equipment or vehicle-mounted scanners and terminals
- Fixed scanners and readers

The engineer's objective should be to select those points and equipment that reliably provide the required data at the lowest cost and with the least disruption to the process. In designing information systems for materials management, the industrial engineer should be alert to potential physical interference from the layout or design of handling and storage equipment and from its operation. At times, it may be necessary to modify the equipment, the layout, or the information systems to achieve the desired results.

CONCLUSION AND FUTURE TRENDS

Current trends in materials management are likely to continue:

- Volume will continue to consolidate among fewer, more capable suppliers.
- Certified receipts will be received in smaller, more frequent lots matched to consumption.
- Items will be produced more frequently and in smaller lots—perhaps in lot sizes of one.

- Finished goods will be minimized as more products are made to order and shipped directly to customers and consumers.
- Nearly instant data acquisition and transmittal will provide the information needed to react almost immediately to changes in demand.

Some industry observers have suggested that we are entering the era of mass customization. More and more items will be produced to individual specification and delivered directly to the customer, with little or no additional cost. Physical systems of production, material handling, warehousing, and distribution must continue to evolve to meet these requirements.

The industrial engineer plays a critical role in translating material management targets, policies, and procedures into working systems. The industrial engineer's ability to develop these methods and systems may determine how well a company can compete in this new environment.

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BIOGRAPHIES

H. Lee Hales is president of Richard Muther & Associates and coauthor with Richard Muther of *Systematic Planning of Industrial Facilities (SPIF)* and the videotape set *Fundamentals of Plant Layout,* produced by the Society of Manufacturing Engineers. Formerly materials and operations manager for a large equipment supplier, Hales has assisted a wide variety of manufacturers in planning and implementing improved operations and facilities. He is a senior member of the Institute of Industrial Engineers and is a past division director for Facilities Planning and Design. He holds B.A. and M.A. degrees from the University of Kansas and an M.S. from the Sloan School, Massachusetts Institute of Technology.

Bruce J. Andersen, CPIM, is an experienced manufacturing and facilities consultant with Richard Muther & Associates. Formerly a production engineer, he has helped leading companies in a variety of industries to make improvements in inventory and production management, facility layout, and the implementation of manufacturing management systems. Andersen is a member of the American Production and Inventory Control Society (APICS) and the Institute of Industrial Engineers. He holds a B.S. in mechanical engineering from Duke University and an M.S. in computer-integrated manufacturing from Georgia Tech.

Source: MAYNARD'S INDUSTRIAL ENGINEERING HANDBOOK

CHAPTER 10.2

MATERIAL HANDLING

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Material handling! What picture comes to your mind when thinking of this topic? It could be a fork truck, a conveyor system, or stevedores loading ships. These are examples of material handling; however, engineered material handling for a distribution system consists of much more than these simple examples. There are many factors to consider when developing or modifying a logistics or distribution material-handling system, such as the material being handled, the required environment (cooler, freezer, etc.), the volume and speed of movement, the type of facility required, and what type of equipment is required with what level of automation.

With the current emphasis being placed on ergonomics, material-handling issues have been given a new importance. This is because it takes equipment and/or modified methods to provide for proper ergonomics in any human-process relationship. This is true in manufacturing, logistics, distribution, and any other process where products or materials have to be placed, assembled, or moved. Material-handling challenges provide an excellent opportunity for an industrial engineer to access and use a set of tools that allow for the development of a new material-handling system or an improvement in an existing system.

Provided here is a practical and useful *guide* that can be used by industrial engineers to aid in the development of solutions to material-handling problems and concerns as related to logistics and distribution. Details on "The 10 Principles of Material Handling," as developed by the College-Industry Council on Material Handling Education, a division of the Material Handling Institute in Charlotte, North Carolina, are included. Also included is an equipment overview section that summarizes the major types of material-handling equipment that are available on the market, provides some application guidelines for their use.

TEN PRINCIPLES OF MATERIAL HANDLING

Over time industrial engineers and other practitioners of material handling have found that there are certain fundamental truths of material handling. These principles of material handling are useful in analyzing, planning, and managing material-handling systems and activities. They are, at a minimum, a basic foundation on which we can begin building experience and expertise in material handling.

As early as 1943 a short set of principles are known to have been documented. The College-Industry Council on Material Handling Education (CIC-MHE) published its first set in 1968. The restated set of 10 Principles (from CIC-MHE) that follow have much in common with these earlier versions. They represent an accumulation of knowledge that has taken place over the years prior to and since 1968. At the same time, the principles have been influenced dramatically by technology and business methodology in distribution and logistics.

The fundamental value of these principles of material handling is that they provide the starting point for identifying problems and developing needs and solutions. They are a benchmark against which existing or planned material-handling activities and systems can be compared and evaluated.

1. Planning Principle

All material handling should be the result of a deliberate plan where the needs, performance objectives, and functional specifications of the methods are completely defined at the beginning.

Key Points:

- The plan should not be developed by the planner/engineer in a vacuum, but with the involvement of all who will use, manage, or otherwise be affected by the equipment to be used.
- Successful implementation of planned large-scale material-handling projects almost always requires a team approach involving suppliers, consultants (where appropriate), and end-user specialists from management, engineering, MIS, finance, and operations.
- The material-handling plan should reflect the strategic objectives of the organization as well as the more immediate needs.
- An important part of the plan is to document existing material-handling methods and problems, physical and economic constraints, and future requirements and goals.
- The plan should promote concurrent engineering of product, process design, process layout, and material-handling methods, as opposed to independent and sequential design practices.
- The material-handling plan should optimize the whole, versus optimizing each part. The sum of optimizing each part individually rarely, if ever, provides the optimal solution.

2. Standardization Principle

Material-handling methods, equipment, controls, and software should be standardized within the limits of achieving overall performance objectives and without sacrificing needed flexibility, modularity, and throughput.

Key Points:

- Standardization means less variety and customization in the methods and equipment employed.
- The planner/engineer should ensure that the selected methods and equipment can perform a variety of tasks in a variety of operating conditions because there is no certainty in predicting the future and the requirements of the system will change over time.
- When considering standardization it should be remembered that this applies to the sizes of containers and other load-forming components as well as to operating procedures and equipment.
- Standardization, flexibility and modularity must not become incompatible.

3. Work Principle

Material-handling work should be minimized without sacrificing productivity or the level of service required in the operation. The measure of work in material handling is flow (volume, weight, or count per unit of time) multiplied by the distance moved.

Key Points:

- Simplifying processes by reducing, combining, shortening, or eliminating unnecessary moves will reduce work.
- Consider each pickup and setdown, or placing material in and out of storage, as distinct moves and components of the distance moves. These should be minimized.
- Good industrial engineering uses process method charts; operation sequences and process/equipment layouts should be used to support the work minimization objective.
- Where possible, gravity should be used to move materials or to assist in their movement while maintaining safety and avoiding the potential for product damage.
- As always, the shortest distance between two points is a straight line.

4. Ergonomic Principle

Human factors in the form of capabilities and limitations must be recognized and respected in the design of material-handling tasks and equipment to ensure safe and effective operations in the system.

Key Points:

- Repetitive and strenuous manual labor should be eliminated with proper equipment selection and implementation that effectively interacts with human operators and users.
- Ergonomics includes both physical and mental tasks.
- The material-handling system and equipment used must be designed so that the safety of people is of utmost importance.

5. Unit Load Principle

A unit load consists of a load that can be stored or moved as a single entity—such as a pallet, a container, or a tote—regardless of the number of individual items (one or many) that make up the load. Unit loads should be sized and configured in a way that will achieve the material flow and inventory objectives at each stage in the supply chain.

Key Points:

- It requires less effort and work to collect and move many individual items as a single unit load than to handle them one item at a time.
- The makeup and size of a load may change as material and product move through manufacturing and distribution channels.
- The most common large-unit loads are both pre- and postmanufacturing in the form of raw materials and finished goods.

- Smaller-unit loads during manufacturing processes, even one-item loads, yield less work-in-process inventory and shorter item throughput times.
- Mixing items in unit loads is consistent with just-in-time and/or customized supply strategies as long as item selectivity is maintained.

6. Space Utilization Principle

All available space must be used effectively and efficiently. Remembering that in material handling, space is 3D and is therefore figured as cubic space.

Key Points:

- Cluttered and unorganized work areas and blocked aisles should be eliminated.
- Maximizing storage density must be balanced with the need for accessibility and selectivity.
- In the transportation of loads within a facility, the use of overhead space should be considered as an option.

7. System Principle

Material movement and storage activities should be fully integrated to form a coordinated, operational system that spans receiving, inspection, storage, production, assembly, packaging, unitizing, order selection, shipping, transportation, and the handling of returns.

Key Points:

- Systems integration should encompass the entire supply chain including reverse logistics. It should include suppliers, manufacturers, distributors, and customers.
- In-process inventories should be kept to a minimum at all stages of production and distribution while keeping in mind considerations for process variability and customer service.
- Information flow and physical material flow should be integrated and treated as concurrent activities.
- Methods should be provided for easily identifying, determining the location and status within facility and supply chain, and controlling movement of materials and products.
- Customer requirements and expectations regarding quantity, quality, and on-time delivery should be met without exception.

8. Automation Principle

Material-handling operations should be mechanized and/or automated where feasible to improve operational efficiency, increase responsiveness, improve consistency and predictability, decrease operating costs, and to eliminate repetitive or potentially unsafe manual labor.

Key Points:

- The existing processes and method should be reengineered before any efforts at installing mechanized or automated solutions.

- Computerized material-handling systems should be considered where appropriate for effective integration of material flow and information management.
- All items that are expected to be handled mechanically or automatically should have features that accommodate this.
- Treat all interface issues as *critical* to successful automation. This includes equipment to equipment, equipment to load, equipment to operator, and control communications.

9. Environmental Principle

The total energy consumption of a material-handling system, along with its impact to the environment, should be an evaluation criterion between alternatives.

Key Points:

- All materials/products used as containers, pallets, and other items to hold/protect unit loads should be designed for reusability and/or biodegradability as appropriate.
- Material-handling system design should take into account the handling of spent dunnage, empty containers, and other by-products of processes or material handling.
- Materials specified as *hazardous* have special needs with regard to spill protection, combustibility, and other risks. These factors should be carefully considered in system design.

10. Life Cycle Cost Principle

A complete economic analysis should account for the entire life cycle of all material-handling equipment and the resulting systems.

Key Points:

- The life cycle costs of any new equipment or method includes all cash flows that will occur between the time the first dollar is spent in planning, right up to the last dollar spent to totally replace the method/equipment.
- Life cycle costs include capital investment, installation, setup, equipment programming, training, system testing and acceptance, operating (labor, utilities, etc.), maintenance and repair, and reuse value and ultimate disposal.
- Preventative and predictive maintenance should be planned for, and its estimated costs along with spare parts costs should be included in the economic analysis.
- Long-range planning for the replacement of the equipment should be accomplished.
- Although quantifiable cost is a primary factor, it is not the only factor in selecting among the alternatives. Other factors that are of a strategic nature to the organization and form a basis for competition should be considered and quantified wherever possible.

MATERIAL-HANDLING EQUIPMENT

Material-handling equipment is any hardware that is used to hold, position, weigh, transport, elevate, manipulate, or control the flow of raw materials, work in process, or finished goods.

This encompasses equipment that can range from the smallest manufacturing jig to the largest transfer truck used for transport. The Material Handling and Management Society has divided material-handling equipment into the following categories:

- Conveyors
- Cranes, elevators, and hoists
- Positioning, weighing, and control equipment
- Industrial vehicles
- Motor vehicles
- Railroad cars
- Marine carriers
- Aircraft
- Containers and supports

Any piece of material-handling equipment that ever existed should fit into one of these categories. However, on examination these categories do not all apply to our scope. The scope here is the discussion of material-handling equipment that applies to logistics and distribution. Therefore, we can narrow these categories down to the following:

- Conveyors—all equipment that moves material/loads between two places in a continuous manner. The equipment exists along the entire path used.
- Industrial trucks—any nonhighway equipment that is used to move material/loads in a batch manner. Typically these span a large area.

These categories are detailed in the next sections.

Conveyors

Conveyors exist that can move a variety of items, from sand and gravel to cartons of finished goods, all the way to pallets of cartons of finished goods. There are two main categories of conveyors:

1. Bulk material-handling conveyor—these include bucket, pneumatic, screw, trough, and vibratory designs. These move material such as loose sand and gravel.
2. Unit load-handling conveyor—these include chute, wheel, roller, belt, live roller, and many others. This conveyor type is used for moving finished goods in bags, cartons, totes, drums, and so on.

Because in distribution we are almost always dealing with finished goods, the discussion here will be about unit load-handling conveyors. Unit load conveyors include roller, wheel, belt, live roller, chain, and others. Conveyors, of the required type, are used to move a unit load over a fixed path between two or more points. The Conveyor Equipment Manufacturers Association defines a conveyor as

> A horizontal, inclined or vertical device for moving or transporting bulk material or objects in a path, predetermined by the design of the device and having points of loading and discharge, fixed or selective . . .

Most conveyors found in distribution systems will fall into one of the following classifications:

- Gravity conveyor
  - Chute
  - Ball transfer
  - Wheel
  - Roller
- Powered conveyor
  - Belt
  - Live roller
  - Accumulation
  - Sortation systems
  - Turntable
  - Transfer car

Gravity Conveyor

According to the "10 Principles of Material Handling" from the College-Industry Council on Material Handling Education a key point of the work principle is

> Where possible, gravity should be used to move materials or to assist in their movement while respecting consideration of safety and the potential for product damage.

The gravity conveyor has an obvious cost advantage and a major advantage in its flexibility to be moved and reconfigured, making gravity the first alternative to consider. The major concerns in applying gravity as a solution are

- Differing pitches needed for various weight loads
- Limited length of lines due to pitch considerations
- Braking control of heavy loads

Gravity Conveyor Summary:

Chute conveyor	Used to move goods by sliding them downhill
Ball transfers	Used to reposition loads manually
Gravity wheel	Used to move cartons in portable applications
Gravity roller	Used to move higher variety of loads, less portable

Chute Conveyor. A chute conveyor (see Fig. 10.2.1) is used to change the position and elevation of a load by having the load slide from top to bottom (entrance to exit). A chute can be configured similar to a straight playground slide and constructed of sheet metal, or it can be configured like the fiberglass water park slides that turn and spiral as they descend. Chutes work well for short distances and for durable loads that can handle the sliding and bumping around. Chutes are often

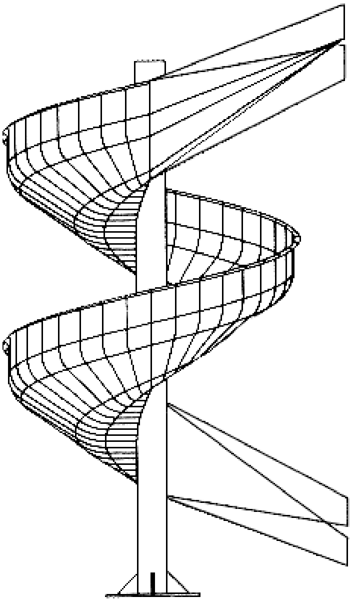


FIGURE 10.2.1 Chute conveyor.

used in distribution systems to lower unit loads from the sortation level to the dock/shipping level. Chutes are easy to use and relatively inexpensive to apply. However, it is hard to control the speed of the loads and often if loads stop on the slide in an accumulation mode, they do not start up well, and it takes the next load coming down the chute to restart it (sometimes causing a jam).

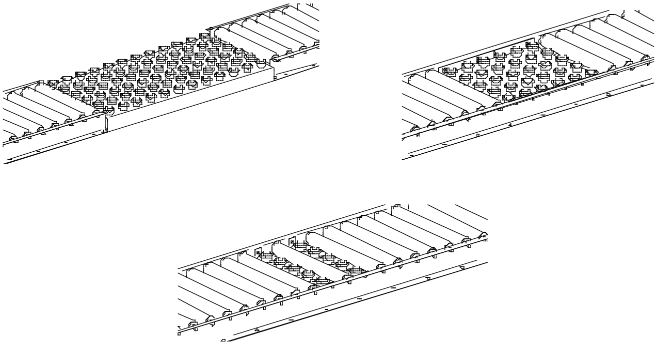


FIGURE 10.2.2 Ball transfers. (*Courtesy of Rapistan Systems.*)

Ball Transfer. A ball transfer conveyor is an array of steel balls mounted in holders that are then mounted on a sheet metal bed or support (see Fig.10. 2.2). The steel ball rollers consist of a large steel ball that is resting on many smaller steel balls in a cup-shaped holder that holds it all together. A ball transfer is normally used as a manual assist in changing the orientation of unit loads. The most common applications are scale operations such as parcel post/ UPS/RPS. Another application is a packing station where a pop-up roller ball transfer can be used to assist movement of heavier loads. The ball transfer is made to pop up through holes in the work surface thus allowing the unit load to be moved easily into position. Then the ball transfer can be dropped below the work surface causing the unit load to rest securely on the surface and not move around. Roller balls can be hard on the bottom of the unit load because of the point-type loading. Soft loads do not work well on roller ball transfers. This should be accounted for in system design.

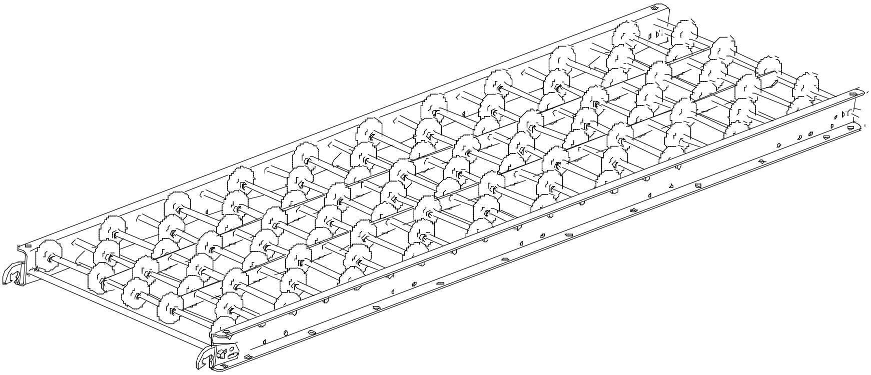


FIGURE 10.2.3 Gravity wheel conveyor. (*Courtesy of Rapistan Systems.*)

Gravity Wheel. Gravity wheel conveyors (see Fig. 10.2.3) are most often referred to as *skate wheel* conveyors because the wheels look like old fashioned steel-wheeled roller skates. The wheels are mounted on axles and the axles are mounted perpendicular to the direction of travel between two side rails that hold it all together. These sections are easily handled and installed. They generally come in 10 ft lengths that are quickly joined to make any length required, or shortened as needed. Skate wheel conveyors also come in curved sections that allow the unit loads to track through the curve because the wheel orientation guides the loads. Skate wheel conveyors are good for loads with hard, durable bottom surfaces. Bags or other soft items generally do not flow well on skate wheel conveyors. A common distribution application is in picking operations and in loading/unloading trailers.

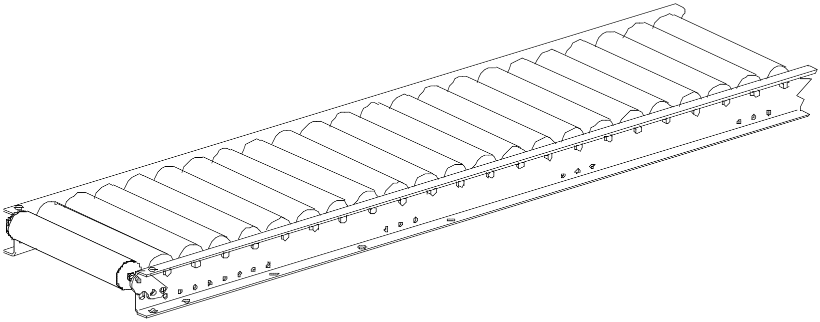


FIGURE 10.2.4 Gravity roller conveyor. (*Courtesy of Rapistan Systems.*)

Gravity Roller. Gravity roller conveyors (see Fig. 10.2.4) are made of rollers that are mounted between frames—as are all roller conveyors, gravity or powered. Roller conveyors are used just like skate wheel conveyors but the rollers allow for more variation in the surface of the unit load. Gravity roller conveyors come in straight, curved, and spiral sections. They can be installed inclined for gravity use or level for manually assisted movement of loads through a work area.

Powered Conveyor

A powered conveyor is a conveyor that is motorized. Powered conveyors can be designed to convey just about anything. The type of powered conveyor to use in an application depends on every factor of the system: the product size and weight, the operating environment, irregular- or smooth-surfaced unit loads, and many others. Prior to choosing a belt, roller, or chain type of powered conveyor, all the possible variables need to be known as far into the future as possible (up to the life of the system). This will allow for the best solution.

Powered Conveyor Summary:

Belt conveyor	Used for inclines/declines and pure transportation
Live roller conveyor:	
Flat belt	Allows adjustable drive pressure
V belt	Allows power to rollers through curves
Cable-driven	Used in more demanding environments

Line shaft	Very flexible drive allowing straights, curves, junctions, and right-angle transfers
Chain-driven	Allows for better load control and heavier loads
Accumulation:	
Continuous	Used for durable product in uniform sizes
Zero Pressure	Used for fragile, less durable goods in various sizes

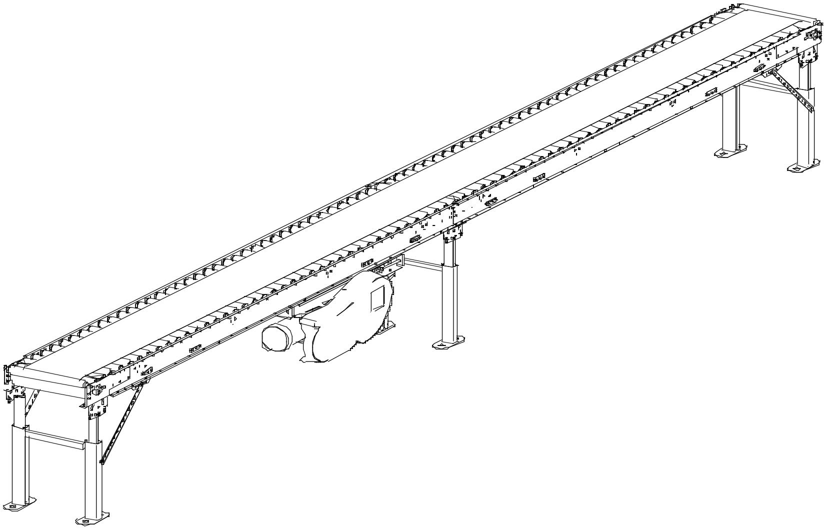


FIGURE 10.2.5 Powered belt conveyor—belt on roller. (*Courtesy of Rapistan Systems.*)

Belt Conveyor. A belt conveyor (see Fig. 10.2.5) consists of a loop of fabric (plastic, metal, rubber, leather, etc.) that is mounted on a drive-and-idler roller. This allows the belt to run between two frames supported by either a sheet metal slider bed or rollers mounted between the frames. Belt conveyors can be used level or for inclines/declines. In package conveyor systems all powered inclines/declines are belt conveyors. Belt conveyors allow for metering of loads, accurate placing of loads, and conveying of loads with soft/irregular surfaces. Belt conveyors are available in curves and spirals.

Live Roller Conveyor. Live roller conveyors (see Fig. 10.2.6) consist of rollers mounted between frames that are driven by various means. Live rollers are used for a much broader range of applications than belt conveyors. They can be used for diverting on to or off of a line of conveyor, accumulation, heavy loads, and challenging environments (dirty, oily, temperature extremes) to minimize the number of drives in a system. Each of these applications may require a different type of drive to the rollers:

- Flat belt (belt-driven)
- V belt
- Cable

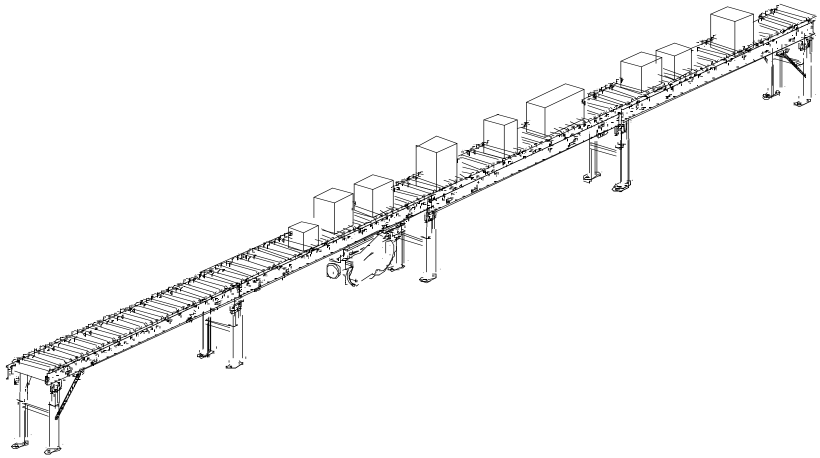


FIGURE 10.2.6 Live roller conveyor. (*Courtesy of Rapistan Systems.*)

- Line shaft
- Chain

These drive mechanisms describe the types of live roller conveyors.

Flat Belt Live Roller. A flat belt live roller conveyor makes use of a narrow flat belt running under the driven rollers between a drive roller and a take-up roller (a spring-loaded roller used to regulate belt tension). The rollers supporting the belt push it up against the bottom of the driven rollers, thus causing contact and drive.

V Belt Live Roller. V belt live roller conveyors work the same as flat belts except for mechanical changes made to support the V belt versus the flat belt. V belt conveyor is often used for curves in live roller systems because the orientation of the V belt allows it to drive rollers in curves (see Fig. 10.2.7).

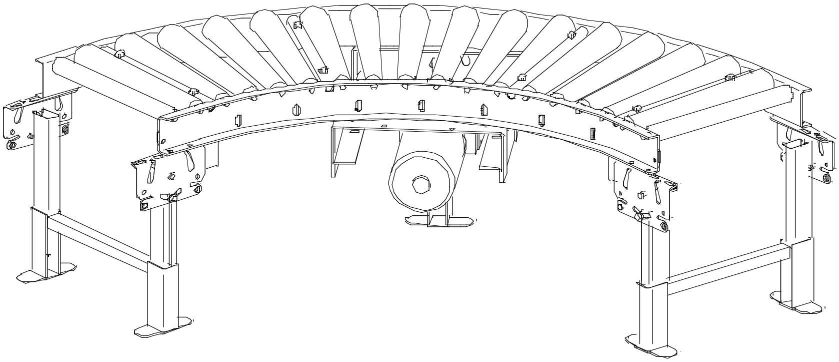


FIGURE 10.2.7 V Belt–driven curve. (*Courtesy of Rapistan Systems.*)

Cable-Driven Live Roller. Cable-driven live roller conveyors are very like V belt conveyors. A cable is used to provide the drive instead of the V belt. The cable is made out of a variety of materials to match the application.

Line Shaft Live Roller. A line shaft live roller conveyor (see Fig. 10.2.8) consists of a roller conveyor with a shaft that is mounted under the rollers down one side of the line. This shaft can

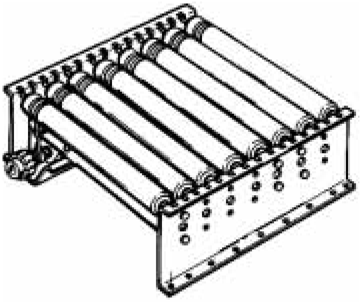


FIGURE 10.2.8 Line shaft live roller conveyor. (*Courtesy of Rapistan Systems.*)

be coupled together with universal joints to allow for curves. Spurs from or to the main line can be accommodated through the use of jackshafts and couplings. Mounted to the spinning shaft are O-rings that are pulled over a groove in the conveyor drive rollers. The direction of twist of the O-rings determines the direction of drive.

Chain-Driven Live Roller. Chain-driven live roller conveyors consist of two types: continuous and roller-to-roller. The continuous is a driven strand of chain that is in contact with a sprocket mounted to each driven roller. In the roller-to-roller conveyor, two sprockets are mounted side by side on the rollers. The end roller is connected to a motor, and each succeeding roller is connected to the next roller in line by a chain. This transfers the drive power from roller to roller. The practical maximum number of chain loops is 80.

Accumulation Conveyor. Accumulation conveyor describes any conveyor that is used to build a queue of unit loads. There are two types of accumulation conveyor available: continuous accumulation and zone or zero/minimum pressure accumulation. These two differ mostly in the mechanical operation of the conveyor hardware. An accumulation conveyor is very important to system design. It is used to control traffic, handle peak inputs without designing everything in the system to handle maximum throughput rate, allow input activities to continue during downstream work interruptions, and consolidate loads that are similar or related in some way.

Continuous Accumulation. Continuous accumulation conveyors accomplish their function by causing the lead load to stop (by positive load stop, pop-up stop, indexing belt stop, etc.), thus starting the accumulation of loads. The accumulation section has a defined length where accumulation can take place safely. This length is determined by the load size, variation in load size, load weight, load durability, and so on. All of these factors determine how much back pressure the loads can handle, thus determining the length of the accumulation section. The controls in the conveyor system are designed to determine when the accumulation section is full. At this point in a continuous accumulation system the power to the drive rollers is either reduced or turned off. When the accumulation needs to be released, the system will restore power/full drive force and deactivate the stop at the beginning of the accumulation zone. This is a slug release because the entire zone releases at the same time.

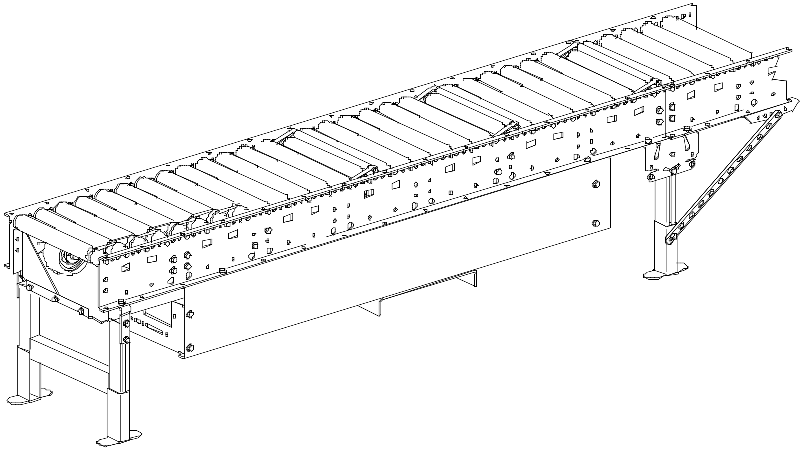
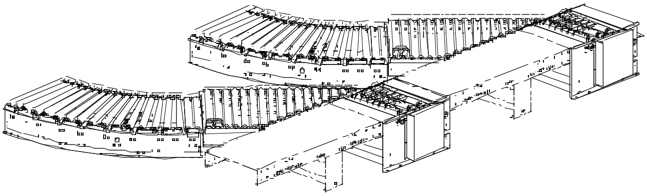
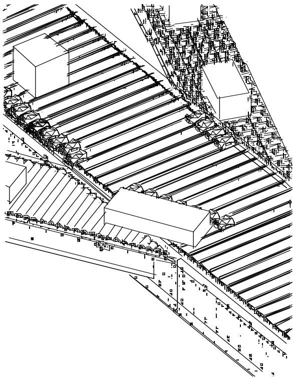


FIGURE 10.2.9 Zero/minimum pressure accumulation conveyor. (*Courtesy of Rapistan Systems.*)

Zone or Zero/Minimum Pressure Accumulation. Zone accumulation (see Fig. 10.2.9) operates exactly as it is named. The conveyor is divided into zones that are usually 24 to 36 inches in length. Each zone has a sensor that is usually a lightweight spring-loaded bar that fits between two rollers (although this varies by manufacturer and often is proprietary). When this bar is depressed by a stopped load it deactivates the previous zone. As in the continuous accumulation, there is a mechanical stop at the beginning of the accumulation line that causes the first load to stop and, in the case of zone accumulation, deactivates the first zone. As each succeeding load is driven into the last zone that is deactivated, it engages the sensor bar and kills the preceding zone. The system will release the first load when desired and with zone accumulation there are two alternatives at this point. The accumulation can release in a slug mode as described previously: multiple zones releasing at one time. The other alternative is that the zone accumulation can release one zone at a time. The initial mechanical stop is released and the first load leaves its zone, thus releasing the sensor bar there, activating the preceding zone, and so on down the length of the accumulation.



Pop-Up Wheel Diverts



Slat Diverts

FIGURE 10.2.10 Sortation system. (*Courtesy of Rapistan Systems.*)

Sortation Systems. Sortation systems (see Fig. 10.2.10) are a natural outgrowth of all the conveyor components that have been discussed thus far. There are quality sorters where an in-line scale weighs a load and compares this actual weight to the theoretical weight of the load. If there is too much variance, the conveyor can be used to divert (sort) these out-of-spec loads to a quality control line. Sortation systems grow from this small start to large-scale distribution systems that can sort hundreds of cartons per minute to literally hundreds of different sort lanes. These systems are used by large freight consolidators and shippers to sort picked and packaged loads to the proper outbound dock door for loading onto trailers for shipment.

In applications where the required throughput is slow to moderate (0 to 30 loads per minute) sortation can be done by roller conveyors with transfers or diverters feeding spurs consisting of powered rollers or gravity rollers/wheels. Where the throughputs increase to higher speeds of 30 to 60 cartons per minute, the sortation can be done with a belt sorter that uses pop-up directional wheels to take control of the load and divert it from the main line. When the throughputs get into the high-speed category of 60-plus cartons per minute (there are manufacturers that can currently sort 280 loads per minute), sortation systems move into sliding shoe, tilt tray, and crossbelt sorters. Sliding shoe sorters use a slat conveyor with shoes that slide across and push or pull the load off the line. Shoe sorters are bidirectional (they can sort to both sides of the line) and perform best when used with hard-bottomed loads. They are capable of high speeds—100 to 200 cartons per minute. Tilt tray sorters consist of a line of trays where the loads are dumped from the trays into sort lanes. They perform well for soft goods and are capable of high speeds approaching 180 cartons per minute. Crossbelt sorters are the newest sortation technology on the market and are capable of 190 to 250 cartons per minute. It is similar to a tilt tray sorter in that there is a discrete "tray" on to which the loads are fed; however, this tray consists of a small belt conveyor. This tray is called a crossbelt because the belt conveyor runs at 90 degrees to the direction of travel of the tray. When the crossbelt reaches the sort location the belt activates and runs the load off the crossbelt. The crossbelt can sort in either direction and can handle soft and hard goods equally well. The high speeds are obtained since, unlike the tilt tray that utilizes gravity to move the load off the tray, the crossbelt drives it off so that the sort locations can be closer together and a much higher degree of control on the load is maintained.

Turntable. Turntables are used to reorient the unit load some degree of angle for the operation. An example would be in an automatic palletizing operation where there is a space constraint. A turntable could be used to turn the unit load 90° from the palletizer exit orientation for take-away. The pallet would move onto the turntable, the turntable would rotate 90°, and the pallet would exit from the turntable.

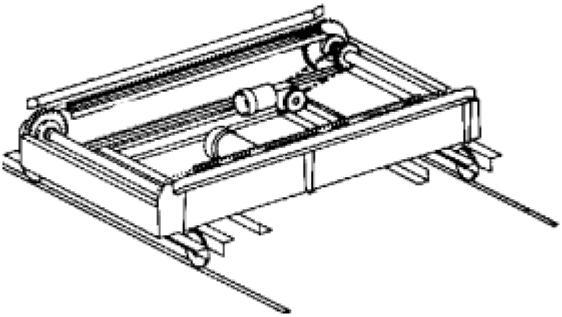


FIGURE 10.2.11 Transfer car.

Transfer Car. A transfer car (see Fig. 10.2.11) consists of a frame with wheels that typically ride on rails. A short section of conveyor is mounted to the frame. The transfer car moves perpendicular to the direction of travel of the loads on the conveyor. They are used in applications where there are multiple input and output lines and throughput is low. The transfer car lines up with an input lane and a load is transferred on to the car. The transfer car then moves to the correct output lane and the load is transferred off the car. The transfer car is then available to make another move. Transfer cars can be either manual or powered.

INDUSTRIAL TRUCKS

Industrial trucks as defined previously are nonhighway equipment that is used to move material/loads in a batch manner. In industry this translates into lift trucks. Lift trucks are designed to lift and transport loads that are too heavy or bulky for safe unassisted handling. *Lift truck* is a term that is used generically to include nonpowered as well as powered equipment. It also includes equipment that is guided, operated, and/or ridden from behind. Lift trucks are generally divided into two categories: low lift and high lift. Low lift trucks raise loads from 4 to 6 in and are generally used only for transporting the loads from one place to another. High lifts raise loads up to a nominal height of 40 ft and are used not only for transport but also for placing loads into storage locations.

Within the low lift and high lift categories there are many classifications with other variables such as drive type, load support, gas or electric power, and manual or automated control. Given all these variables, fork trucks can be divided into these major types: hand trucks, powered industrial trucks, and automated guided vehicles (AGVs).

Hand Trucks

Hand trucks are devices with wheels that have a platform, forks, or other surface or tool for supporting a load while transporting it manually. The most basic and well known is the two-wheeled hand truck or dolly such as would be used to move a home appliance or a stack of cartons. Hand trucks are often used on shipping and receiving docks to move loads on to and off of trucks. There are hand trucks that have been designed to handle a specific kind of load. Two examples are the appliance dolly and a drum-handling hand truck.

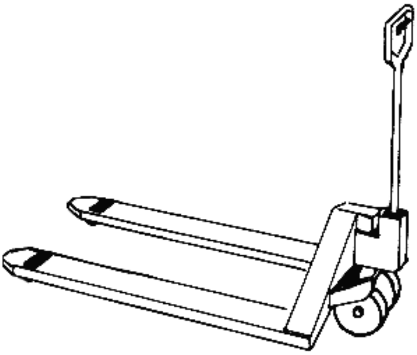


FIGURE 10.2.12 Hand pallet jack.

The next type of hand truck is a pallet jack (see Fig. 10.2.12), often called a hand pallet jack to distinguish it from powered equipment. A hand pallet jack is designed to handle pallets or similar type loads. The truck consists of two forks that when lowered will fit into the fork pockets of pallets (or under other skid-type loads). The forks have wheels near the ends that (along with a third wheel mounted at the bottom of the handle) support the pallet jack and load. The handle of the pallet jack is also connected to a hydraulic pump that activates as the handle is pumped up and down. This serves to raise the forks to pick up the load for transport. When the operator has moved the load to its destination, he or she pulls a release lever (located on the handle) for the hydraulic pressure that drops the forks so that the pallet jack can be removed from under the load.

Another common hand truck is the platform truck, which comes in many forms. Typically it has a low platform supported by three to four wheels, two of which are usually fixed while the remainder swivel to allow the platform truck to be steered. A platform truck on which all the wheels swivel is referred to as a dolly. It has applications where it may be necessary to move the dolly in any direction. One negative of this type of dolly is that with all the wheels able to turn, the dolly is often hard to steer straight over long distances.

Powered Trucks

Powered trucks describe vehicles that have motorized, electric, or internal combustion that provides lifting and driving power. The Industrial Truck Association has established a set of classifications for industrial trucks (see Table 10.2.1).

TABLE 10.2.1 Industrial Truck Association Lift Truck Classifications

Class	Description	Applications	Typical load capacities (lb)	Typical lift height (ft)
I	Electric motor rider trucks	Indoor, general purpose	2,000–12,000	16–25
II	Electric motor narrow-aisle trucks	Indoor, narrow aisle and very narrow aisle	2,000–4,500	Up to 40
III	Electric motor hand trucks	Indoor, general purpose	4,000–8,000	NA
IV	Internal combustion, cushion tire	Indoor and outdoor general purpose	2,000–15,000	Up to 20
V	Internal combustion, pneumatic tire	Outdoor, general purpose, paved surfaces	2,000–15,000	Up to 20
VI	Tow tractors	Indoor, long distance	NA	NA
VII	Rough-terrain lift trucks	Outdoor, construction sites	4,000–20,000	Up to 40

The most notable item is that there are two types of power for lift trucks: electric and internal combustion (gasoline or natural gas). Another item to note is that there are trucks designed for indoor and outdoor applications. In lift truck terminology, classifications I, IV, and V are usually referred to as *counterbalanced trucks* (see Fig. 10.2.13).

Counterbalanced trucks are designed to minimize their overall length to allow for greater maneuverability and a narrow aisle requirement—less space required for right-angle stacking. To accomplish this, the trucks are designed so that the load is carried in front on forks or another type of attachment. This load is carried by the wheels located just behind the mast, which act as the pivot point of the truck. This design causes the portion of the truck behind the wheels (operator, battery, engine, etc.) to act as the counterbalance of the load. Counterbalanced trucks are available in sit-down and stand-up configurations, with the higher load capacity trucks being the sit-down variety.

The debate between internal combustion and electricity for power breaks logically on where the truck is used. In an indoor distribution environment electric power fits best. These trucks are quieter, simpler to maintain, and do not emit potentially noxious fumes. For out-

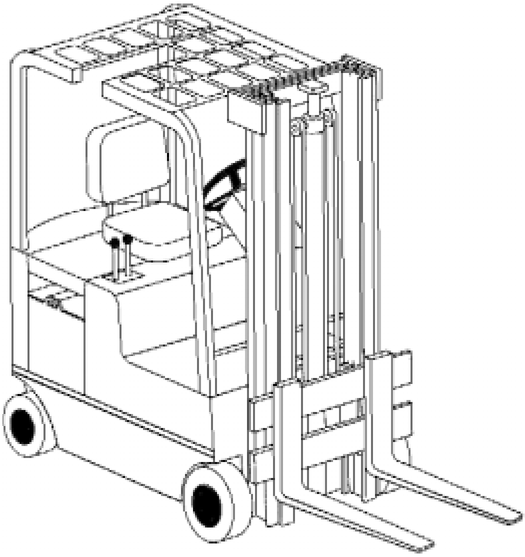


FIGURE 10.2.13 Counterbalanced fork truck.

MATERIAL HANDLING

door and high-capacity applications, internal combustion rules the day. This is because electric trucks do not operate well in the weather, and the power requirements of hilly and uneven terrain are handled much better by an internal combustion engine than an electric motor.

Class II Industrial Trucks. Looking at class II industrial trucks (see Table 10.2.1)—electric motor narrow-aisle trucks—we must first define *narrow-aisle.* A standard width aisle is 12 to 15 ft; this amount of aisle will provide room for almost all trucks to perform a right-angle stack with plenty of clearance. A narrow-aisle (NA) is 10 to 12 ft. For this aisle width, the chassis of the trucks needs to be shortened in order to perform a right-angle stack with ample clearance. To shorten the chassis the driver is usually put in a stand-up position. There is also a category of aisle width called very-narrow-aisle (VNA), this is an aisle width of 5 to 10 ft. VNA fork trucks are modified in function so that the truck does not perform a right-angle turn in the aisle, but the load is turned and moved into the storage rack.

Class II Industrial Trucks Summary:

Order picker	Places operator at storage level for picking/replenishing/inventorying
Straddle truck	Allows narrow aisle with uniform load widths
Reach truck	Allows narrow aisle with varying load widths
Swing mast truck	Allows narrow aisle by swinging load instead of truck
Turret truck	Turns load without turning truck, high-speed/high-volume applications
Side loader	Allows handling of long loads (pipe, steel stock, etc.)

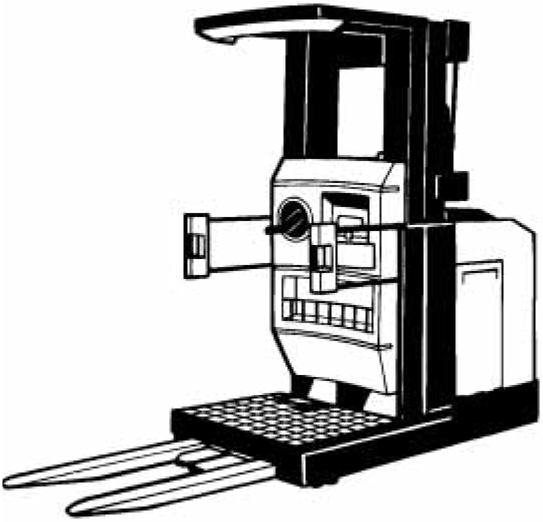


FIGURE 10.2.14 Order picker truck.

Order Picker. An order picker truck (see Fig. 10.2.14) has the operator's platform and controls attached to the mast of the truck. The forks are attached to the platform. This truck is not designed to move, stack, and/or store pallets but to move up and down the aisle with the operator picking orders or replenishing locations. The operator controls the truck from the platform, and by placing a pallet or another container on the forks the operator can then move down an aisle and raise up to a location to replenish, pick, or inventory a location. To have better control of the truck, wire or rail guidance is often used. This allows the truck to move faster through the aisle and also increases the operator's comfort level when moving vertically and horizontally simultaneously. This reduces cycle times for moving between locations.

WIRE GUIDANCE: Wire guidance is an automated system for controlling the direction of a VNA truck. A wire is placed just below the floor surface with a signal running through it that a receiver on the fork truck tracks. Automated controls on the truck use the tracking information to send steering inputs to the truck.

RAIL GUIDANCE: Rail guidance is an application for guiding a truck through an aisle. Angle iron is lagged to the floor down the length of the aisle. The truck has casters mounted on all four corners that engage the angle iron (rail) and keep the truck headed straight down the aisle.

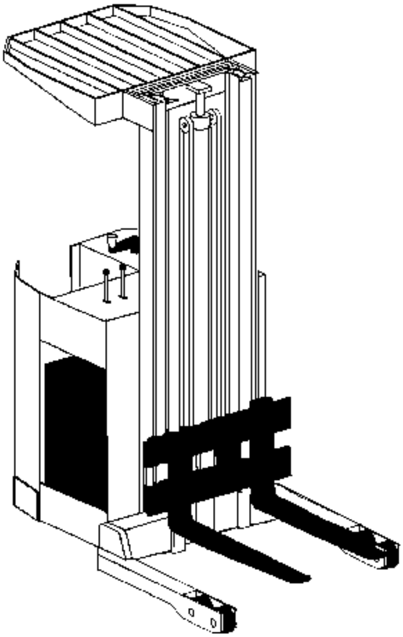


FIGURE 10.2.15 Straddle truck.

Straddle Truck. A straddle truck (see Fig. 10.2.15) is constructed with wheels that are mounted on arms (outriggers) out in front of the mast. The forks operate between these outriggers so that the outriggers have to straddle the load to pick it up. An alternative to straddling the load is for the load to be placed on a platform or stand so that the outriggers can go under the load. In most cases, the bottom level of the pallet rack is placed on a pair of beams up off the floor for ease of operation.

Reach Truck. A reach truck (see Fig. 10.2.16) is simply a straddle truck with a special mechanism on the mast that the forks and backrest are mounted to. This mechanism is a pantograph and it allows the forks to be extended beyond the outriggers to pick up and set down loads. This permits the truck to pick up a load that is too wide to straddle, as well as eliminates the need for bottom beams in a pallet rack.

Double Deep Reach Truck. This is simply a reach truck that has a double pantograph mechanism attached to it (see Fig. 10.2.17). The truck can store loads two pallets deep in a pallet rack (double deep rack), increasing the cubic utilization of the storage area.

Swing Mast Truck. Swing mast trucks (see Fig.10. 2.18) are designed with a special mast that is mounted on a pivot that allows the mast to swing out at a right angle and place a load in the pallet rack. This truck can operate in a very narrow aisle since the aisle does not need to be much wider than the truck and the load. The typical application operates in a 6- to 7-ft-wide aisle. These trucks are very heavy since they have to be counterbalanced to handle the mast and load pivoted out at 90°. These trucks can also pivot only one direction (to the right), so the operator has to consider which side of the aisle is needed prior to entering the aisle.

Turret Truck. A turret truck (see Fig. 10.2.19) has the ability to move loads into rack storage without having to turn. This is accomplished by mounting the forks on a device called a turret that can rotate the load through 180°. When the load is rotated into the desired storage direction, the forks traverse toward the location and deposit the load. Human-up and human-down versions of the turret truck are available. The human-up version has the advantage of placing the operator right at the load storage location. This allows him or her to align the load with the location easily and use the truck as an order picker. Human-up order pickers are rec-

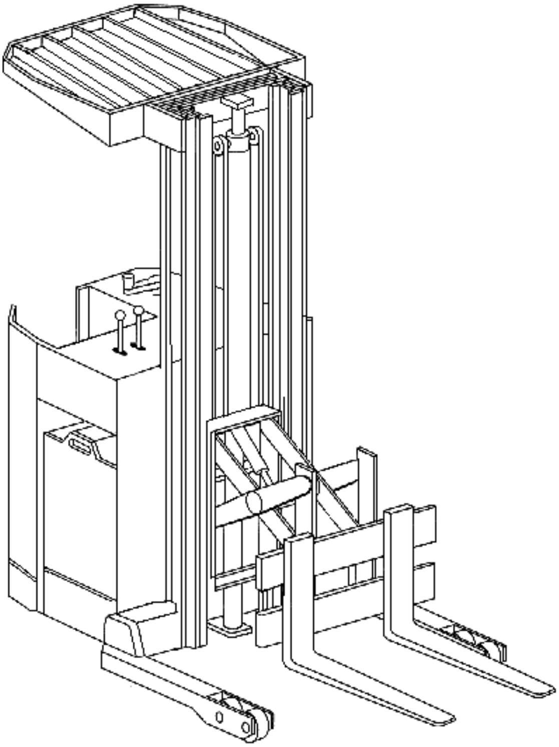


FIGURE 10.2.16 Reach truck.

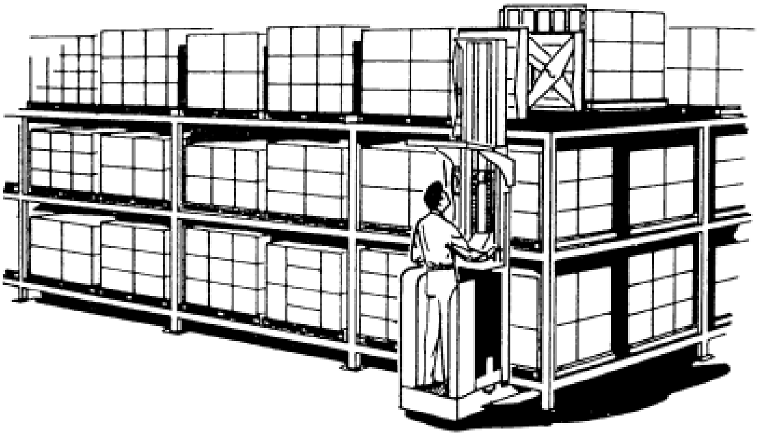


FIGURE 10.2.17 Double deep reach truck.

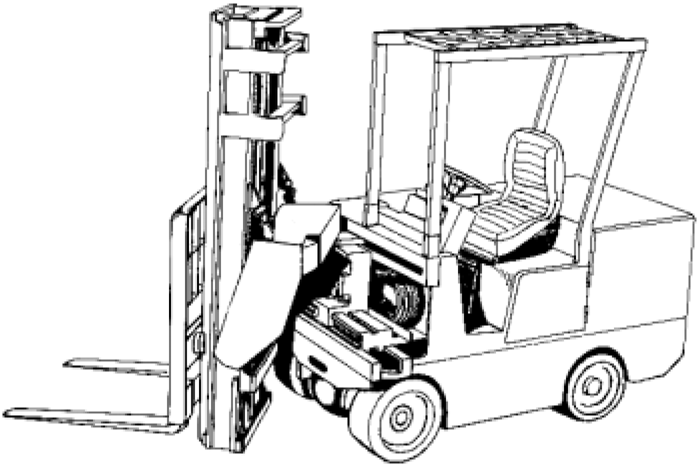


FIGURE 10.2.18 Swing mast truck.

ommended when the height of storage exceeds 20 to 25 ft because of the aforementioned advantages. The human-down turret truck has higher operating speeds, improving throughput if the application requires this. The human-down turret trucks require a device that aids the operator in selecting the load height for the tallest locations.

Side Loader Trucks. A side loader truck (see Fig. 10.2.20) is designed to handle long loads from the side that are typically stored in cantilever racking. The trucks travel down the aisles with the load carried parallel (lengthwise) to the aisle. The forks are extended into the rack by either a pantograph or a rolling mast design. In most applications the trucks are guided in the aisle automatically, by wire or rail.

Class III Electric Motor Hand Trucks

Class III Industrial Truck Summary:

Walkie	Allows moving heavier loads (than can be moved manually) at walking speeds and distances
Walkie/rider	Allows moving heavier loads longer distances
Transporters	Allows moving multiple loads simultaneously
Walkie stacker	Allows stacking of loads with walkie benefits

Powered Pallet Jacks. These are powered versions of the manual pallet jacks previously described (see Fig. 10.2.21). There are versions of this truck for which the operator must walk behind (walkie) and versions on which the operator can ride (walkie/rider). These also come in versions that have double-length forks, often called transporters, that can carry as many as four pallets (two double-stacked side by side). This category of powered truck is inexpensive and very useful in shipping and receiving areas. They can go onto trailers to load and unload. The double-length fork models are very efficient transporters for moving pallets from dock areas to putaway or vice versa. There is even a version of the walkie pallet jack that can stack pallets, but its height capacity is less than 15 ft. This truck is called a walkie stacker; it has limited use but is often just the right truck.

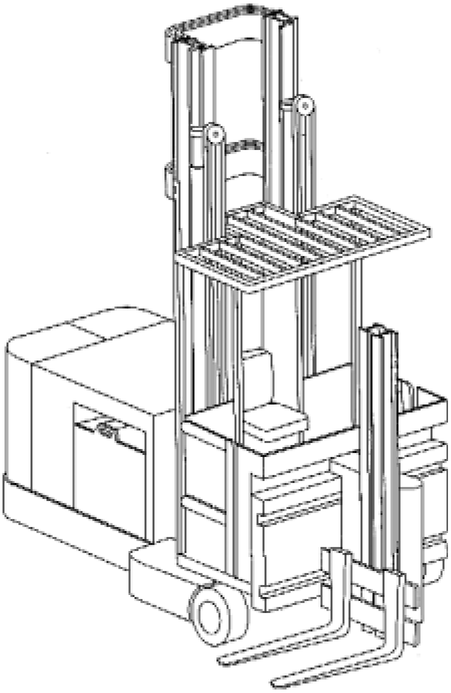


FIGURE 10.2.19 Turret truck.

AUTOMATED GUIDED VEHICLE SYSTEMS

Automated guided vehicle (AGV) systems provide just about the highest level of automation in a material-handling solution. Imagine a system that automatically picks up and delivers loads through an operation. As an example: A receiver has just completed receiving a unit load of goods and accepted it to go to storage via radio frequency (RF) computer device; this triggers the AGV system to send a vehicle to this pickup/delivery (P/D) position; the vehicle is scheduled and dispatched automatically with the system knowing what type of vehicle to send by what was received; the vehicle arrives and picks up the load (this could be automatic or could require operator input); the vehicle then delivers the load to its destination. This example highlights the four major components of an AGV system: vehicles, P/D stations, guidance system, and an AGV control system.

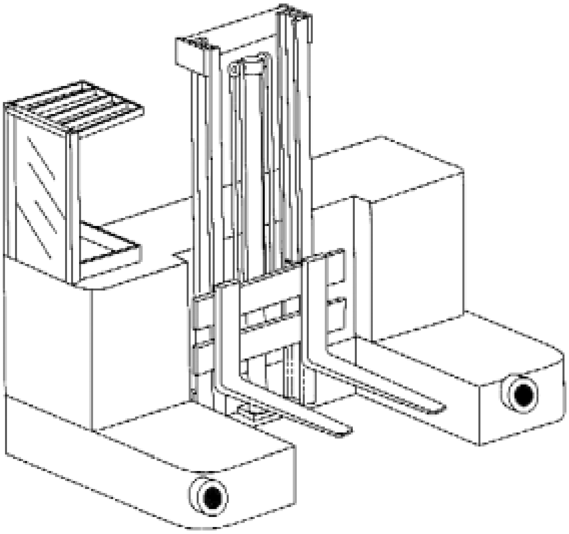


FIGURE 10.2.20 Side loader truck.

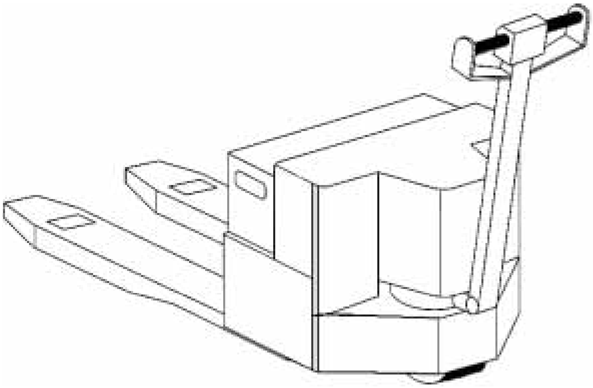


FIGURE 10.2.21 Powered pallet jack.

AGV Summary:

Tractors	Used to engage and tow loads
Pallet vehicles	Used to pick up and deliver pallet loads
Unit load carriers	Used to pick up and deliver unit loads
Light load carriers	Used to move light loads (mail, drugs, etc.) in an office/light industrial environment

Vehicles

AGVs come in all varieties; if it can be thought of, someone has probably designed it (see Fig. 10.2.22). In general, AGVs fall into one of four types: tractors, pallet vehicles, unit load carriers, and light load carriers. Tractors are used to pull loads that most often consist of trailers that have been loaded with unit loads. Pallet vehicles are very similar to fork trucks, but they can load/unload automatically, even to a pallet rack. Unit load carriers are typically designed to carry the load on their top—often capable of carrying more than one unit load. The unit load top is often a bed or conveyor that interfaces with the P/D station to move loads on and off. Light load carriers are vehicles that are usually loaded and unloaded manually. They carry light loads such as mail in a large office complex. Light load carriers have even been used in hospital applications for drug delivery from a centralized pharmacy to the individual nurses' stations.

PickUp/Delivery (P/D) Stations

P/D stations are the point in the system where the vehicle interfaces with unit loads to pick them up or drop them off. P/D stations can be as simple as a square painted on the floor where a pallet is placed by an operator for pickup. They can also be as complicated as a section of a special conveyor that interfaces with a unit load vehicle to move loads on and off a vehicle.

Guidance System

An AGV must have an interface with the control system that allows the vehicle to move through the facility automatically. To accomplish this an AGV has an advanced guidance sys-

MATERIAL HANDLING

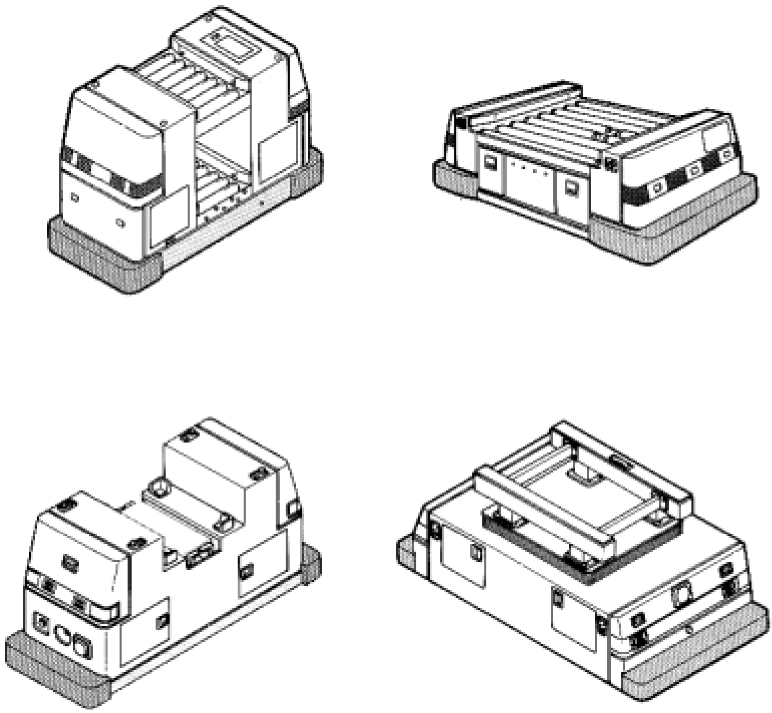


FIGURE 10.2.22 Automated guided vehicles.

tem. The simplest of AGV control strategies calls for an operator to key a destination code into an onboard terminal. The AGV then travels to this destination with the control system directing the guidance system. There are currently five main techniques for guiding AGVs:

1. *Inductive wire guidance.* This is most commonly used for large load AGVs and is very similar to the wire guidance used by narrow aisle fork trucks. An onboard sensing device tracks an electromagnetic field that is provided by a small wire recessed into the floor. This system requires smooth floors, and the wire must be continuous. For turns it is possible for the wire to be installed at a right angle. The truck will accomplish a turn by leaving the wire and executing a programmed turn until it reconnects with the wire. This permits an easier and less costly installation.
2. *Optical guidance.* Optical guidance uses tape, paint, or other reflective material to establish the path. A light source on the AGV illuminates the path for an optical sensor also onboard the AGV. Optical guidance paths are easy to install and modify, and are easily maintained and changed as required. However, the optical path is not as durable as in-floor wire since it is placed on the floor surface; therefore, optical guidance is most suitable for clean industrial and office environments.
3. *Self-guided vehicle.* This form of navigation is a combination of dead reckoning, with position updating being provided by a laser beam that reflects off known reflective bar codes or targets. This is the easiest hardware to install for guidance, but it must be done thoroughly, and the safety features of the AGV for collision avoidance must be in prime working order. A self-guided system can generate an alternate route if the chosen path is blocked and does not clear in a predetermined amount of time.

4. *Chemical guidance.* This consists of a phosphorus-type paint that marks the path. It works like the optical guidance with a black light as the light source. The advantage of chemical guidance is that the path is invisible to the eye.
5. *Vision system.* This is the newest navigation system on the market. It consists of an onboard camera that compares the view ahead with one that has been preprogrammed. Using the results of this comparison, the navigation control system keeps the vehicle on track.

Control System

An AGV control system is the program sitting on top of the sum of the previous three components and providing overall control. Control systems for AGVs run the full range of complexity from simple one- or two-vehicle systems that are manually called and dispatched, to a fully automatic system that dispatches, guides, and schedules AGVs automatically. The more advanced the system the more critical it is for the control system to communicate directly with the AGV. The method for this communication can take the form of inductive wire, floor devices, radio frequency transmission, and optical infrared.

Two other very important functions of the control system are routing and traffic control: the route the vehicle(s) is to use and what happens when two vehicles get into the same area. With some forms of communication (i.e., inductive wire) only one vehicle in a zone can be controlled (communicated to) at a time. If there are two vehicles in the zone, both will try to execute the commands given by the control system.

RESOURCES

Many resources are available to aid in developing solutions to material-handling problems. They range from equipment vendors and consultants to system integrators, catalogs, and the Internet.

Some of the best information can be obtained through participation in professional organizations. It is here that opportunities exist to meet and talk with others that work in industry to develop relationships for networking. Through these networks of professionals much information can be gathered to work toward finding solutions for handling problems. Many times I have talked with someone that had a very similar problem, and I was able to learn from their experiences and develop a solution much faster and with better results. There are many professional organizations in existence today. Some of these are

- International Warehouse Logistics Association
  1300 West Higgins Road, Suite 111
  Park Ridge, IL 60068
  (708) 292-1891
  www.warehouselogistics.org
- Institute of Industrial Engineers (IIE)
  25 Technology Park
  Atlanta, Norcross, GA 30092
  (404) 449-0460
  www.iienet.org
- Warehouse Education and Research Counsel (WERC)
  1100 Jorie Boulevard, Suite 170
  Oak Brook, IL 60521
  (708) 330-0001
  www.werc.org

- Material Handling Institute of America (MHIA)
  8720 Red Oak Boulevard, Suite 201
  Charlotte, NC 28217
  (704) 522-8644
  www.mhia.org
- American Production and Inventory Control Society (APICS)
  500 West Annandale Road
  Falls Church, VA 22046
  (703) 237-8344
  www.apics.org

Another excellent source of information is trade journals. These are easily obtained, often free of charge if you meet certain requirements, from their publishers. These journals have articles dealing with equipment, solutions to problems, case studies of applications in industry, and so on. They are also full of ads for equipment, consultants, and the like. Some of these journals are

- *Modern Materials Handling*
  Cahners Publishing Company
  275 Washington Street
  Newton, MA 02158-1630
  www.mmh.com
- *Materials Handling Management*
  Penton Publishing, Inc.
  1100 Superior Avenue
  Cleveland, OH 44114-2543
  www.mhmweb.com
- *IE Solutions*
  Institute of Industrial Engineers
  25 Technology Park
  Atlanta, Norcross, GA 30092
  www.iienet.org

The Internet provides almost an overabundance of information. It is easy to become overloaded with information on the Web. And there are some excellent sites for seeking information on material handling. A partial list of these includes

Industry:

- www.manufacturing.net—A web site that contains contacts and information for a wide range of manufacturing resources, suppliers, and associations.
- www.MHIA.com—The web site for the Material Handling Industry of America.
- www.WERC.com—The web site for the Warehousing Education Research Counsel.

Equipment vendors:

- www.alvey.com—This is the web site for a conveyor and material handling solutions supplier. It contains good information on their product line and services.

- www.Rapistan.com—This is the web site for the largest domestic supplier of conveyor equipment in the United States. It contains a fair amount of information on equipment and provides contact information for gathering more information.
- www.YALE.com—This is the web site for Yale Industrial Trucks. This site contains a good level of detail for equipment information, as well as photographs and illustrations.
- www.Crown.com—This is the web site for Crown Fork Trucks. It contains some fork truck information and illustrations, as well as detailed contact information.

This is by no means a complete list of contacts for information dealing with material handling in distribution/logistics. They are too numerous to list completely and change every day. These few will get you started on a path that will quickly provide you with an abundance of information. The real trick is to know when to stop looking and apply what has already been learned. This is the subject of another whole book and not within the scope of this chapter.

SUMMARY

The purpose of this chapter was to provide the industrial engineer with a reference chapter on material handling. I have tried to present the most common types of material-handling equipment in use in a distribution environment. Some practical application issues and the functionality of the main categories of conveyors and industrial trucks were presented. An excellent introduction to material handling using "The 10 Principles of Material Handling" as developed by the College-Industry Council on Material Handling Education was presented in the first half of the chapter. This should provide The industrial engineer with enough reference material to get an excellent start on developing solutions for material-handling challenges.

FURTHER READING

Tompkins, J. A. and Dale Harmelink, *The Distribution Management Handbook,* McGraw-Hill, New York, 1994.

Tompkins, J. A. and Dale Harmelink, *The Warehouse Management Handbook,* McGraw-Hill, New York, 1988.

BIOGRAPHY

David A. Lane is an industrial engineer for The Stellar Group, an architectural and engineering firm providing facility design and development services worldwide. Lane graduated from North Carolina State University in 1984 with a B.S. in engineering operations. His work experience has been concentrated in material handling issues in manufacturing and distribution. He has worked with Burlington Industries, JCPenney, E-Systems (Raytheon), Tompkins Associates, AT&T, Hillshire Farm, Bryan Foods, Polaroid, Royal Home Fashions, and Rapistan Systems. He is a senior member of IIE and a member of the Warehouse Education and Research Council.

Source: MAYNARD'S INDUSTRIAL ENGINEERING HANDBOOK

CHAPTER 10.3
WAREHOUSE MANAGEMENT

Herbert W. Davis
Herbert W. Davis and Company
Fort Lee, New Jersey

The modern distribution center is very different from the storage warehouse of pre-1960 multilevel industrial practice. Today's facility is large, high, and complex. A typical warehouse of the late 1990s may be 200,000 to 500,000 square feet in floor area, have stacking heights of 25 to 35 feet, have tens of millions of dollars of installed equipment, employ hundreds of people, and ship a daily throughput rate of several thousand tons of material.

These complex facilities are the direct result of the application of industrial engineering concepts and practice to the multicompany, multifacility supply chains that move finished products from source to customer. This chapter describes the functions of the warehouse and the use of industrial engineering techniques in the design and operation of the facility. Special attention is focused on the new computerized warehouse management systems that have been developed in the 1990s to sharply improve productivity and accuracy in the warehouse and to aid in managing the flow of materials, both within the facility and in the transport system that delivers products to customers. Without bar code scanning, product identification, and warehouse management software, these new warehouses would not be viable in today's low-inventory, highly competitive logistics environment.

WAREHOUSING LEVELS

The storage and handling of materials is an important function in manufacturing and distribution. Storage levels normally used in the industrial process are as follows:

- Raw material stores (chemicals, bar stock, component parts)
- Tool cribs (molds, dies, cutting tools)
- Maintenance supplies (paper, oils, electrical, and plumbing repair parts)
- In-process materials (items stored between manufacturing operations)
- Plant finished-goods warehouses
- Public distribution centers
- Private distribution centers
- Bonded warehouses (usually for imported goods held while awaiting the payment of customs charges or for transfer to another country; may be for products on which local or federal taxes have not yet been paid)

In the general case, storage and warehousing occur in or near either the plant or the market. Seldom are warehouses located between plants and markets. Plant-located facilities either serve the plant operations (raw materials and tool cribs, for example) or are a major customer shipping point. The plant warehouse may also be the backup point to resupply a field distribution system. Market-located facilities are positioned to supply customers with the company's products. These distribution centers may store the output from a number of plants. The customer can order products made by several plants and vendors and receive a single shipment from the distribution center. Proper location planning can result in fast, complete delivery of a customer's order, which tends to increase satisfaction and future volume.

Most warehouses are operated privately by companies for their own materials and products. There are many public warehousing companies, however, that offer space and labor on a for-hire basis. During the past three decades, the public warehouse industry has increased in size, complexity, and the range of services offered. The warehouse, for example, might contract to do price ticketing, assembly and repacking, labeling, inbound material consolidation, outbound customer freight consolidation, and order receipt and entry. Public facilities with a tie-in to transportation carriers can also offer product tracking and status reporting. These services, added to an already high level of warehouse productivity, have resulted in public warehousing growth rates higher than that of company-operated facilities.

WAREHOUSE DESIGN

The methods used to design the materials flow, handling, and storage activities and to control labor productivity in a modern distribution center are similar to industrial engineering practice in a manufacturing plant. There are a number of special conditions, however, in distribution facility design and operations that could be helpful to the industrial engineer in designing the facility.

Building Considerations

Many warehousing facilities are located inside manufacturing plants. In such cases, it is common to find that the building is constructed to meet manufacturing needs (stacking heights, floor storage arrangements, bay sizes, etc.). This practice results from the common use of space by both activities. Manufacturing frequently expands into the space occupied by warehousing.

In freestanding distribution centers and on a few plant sites, the warehousing facility is designed to fit the unique characteristics of the distribution system. For example, modern stacking equipment can economically operate at heights of 40 to 85 feet or more. Some equipment can right-angle stack in a 5-foot-wide aisle. Other equipment may be secured to the building structure or the storage racks. The need for such dense storage patterns results in the design and construction of special-purpose buildings that are not generally useful for manufacturing. In designing the modern distribution center, the industrial engineer must consider the following factors.

Material Flow. The building can have a straight-through flow with receiving on one end and shipping on the other. Another popular approach is a U-shaped flow with common receiving and shipping areas. This method concentrates most of the building employees and activities for better control. Both methods are effective; the best choice can be determined based on economic analysis and site configuration.

Levels. Older facilities—and some very modern distribution centers—are frequently multilevel. Storage, however, is most efficient when concentrated on one floor level with a high stack height. Receiving, shipping, and packing operations, on the other hand, seldom require high ceilings. Normally, horizontal travel is less costly than vertical, leading to the current interest in single-level warehouses. The industrial engineer must reconcile these factors in preparing the design.

Bay Dimensions. The storage pattern is a crucial factor in distribution center design. The buildup of storage spots and access aisles dictate the bay dimensions. Proper design can result in efficient or optimum bay dimensions. A *bay* is the floor area bounded by the building support columns. Forty years ago, it was not uncommon to work with 3-foot-diameter concrete columns on 20-foot centers. In this situation, storage patterns were relatively inefficient. Current construction allows about 8 to 12 inches for steel columns, spaced 30 to 60 feet on centers. Figure 10.3.1 is an example showing how pallets and pallet racks and the associated forklift access aisles are accumulated to determine bay dimensions. Note that the storage pattern is determined first. Then the column spacing is calculated to locate columns within the rack or storage structure. The final spacing may be any multiple that minimizes column space loss while providing a lower-cost, steel-frame roof structure. The final dimensions are decided by building cost calculations designed to balance the cost of lost space with that of extra-long steel members.

Ceiling Heights. The vertical distance between floor and lowest structural obstruction in a modern distribution center is determined by the storage stack height and the clearance needed for water dispersion from sprinkler heads. The storage area may contain storage racks on which palletloads of material are placed. There may be bulk stacks where palletloads are continuously stacked to the crushing limit. Pallet racks, however, normally are used in buildings with very high stack heights, because current lift equipment is capable of safely stacking much higher loads than product crushing limits or stability would permit. A typical ceiling height derivation is shown in Fig. 10.3.2.

Mezzanines. Because most modern distribution centers are constructed on a single level, the use of temporary and/or permanent mezzanines is an important building option. Mezzanines may be constructed with steel grating supported by storage racks, special columns, or

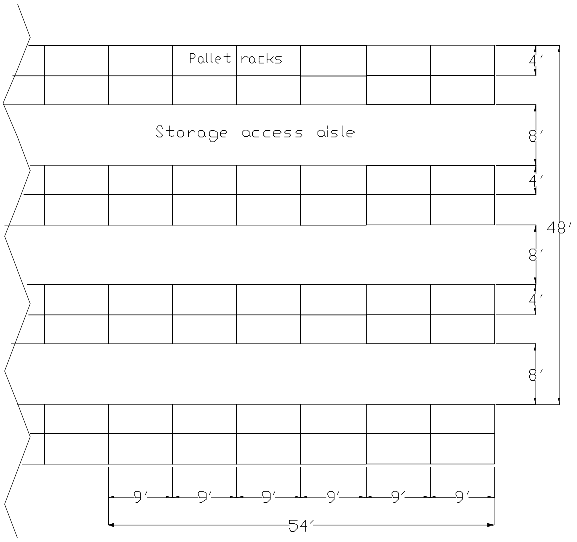


FIGURE 10.3.1 Typical bay dimensions.

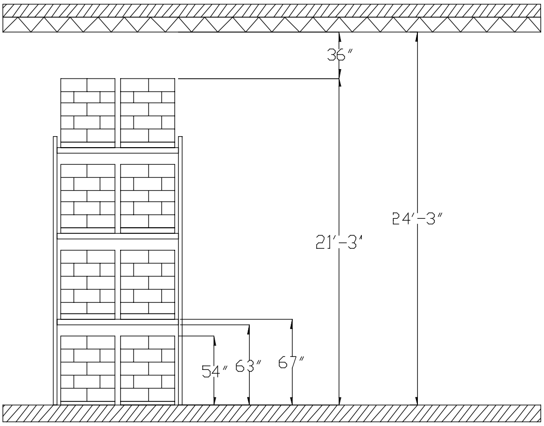


FIGURE 10.3.2 Ceiling height derivation.

building columns. They are used to more fully utilize the cubic space in a building. Typically, a warehouse may have storage covering 50 to 75 percent of the floor area. The other operations such as receiving, counting, marking, packing, and staging may total 50,000 square feet or more, but may not effectively utilize the warehouse height of 30 or more feet. Thus, two or three overhead levels might be constructed to house these activities more efficiently.

Number of Truck Doors. Doors are expensive, in both construction costs and energy loss. Determining the right number of truck and utility doors is complex, frequently requiring the use of simulation. Doors may be single-purpose (receiving, shipping, over-the-road trailer, etc.) or multipurpose to fill all needs. Most warehouses are built with the floor 48 inches above grade and pavement. This provides for forklift access to typical highway trailers. Special-purpose docks for vans (24 inches) and ground-level access for inside loading may be provided.

A method to accurately estimate the number of doors needed requires accumulating a record of truck arrivals (or unloading) and a separate record of outbound loads. The industrial engineer needs to measure the average loading or unloading time for a sample time period. Given the average arrival and departure frequency and the average load/unload service time, queuing theory can be employed to determine the appropriate number of docks. Queuing tables are available to simplify calculation.

Length-to-Width Ratios. In many cases the available land dictates the general configuration of the warehouse building. Given unlimited sites, however, the ratio of building length to width is a useful design element. The selection depends on the desired materials flow and the handling/storage method used.

U-Shaped Flow. The docks may be on one common wall to maximize control and cross-utilization of personnel. Buildings tend to be constructed square or to a 3:2 length-width ratio in these circumstances to minimize internal movement. Expansion is usually on the back wall opposite the truck dock wall. This provides for low-cost additions since the expansion need only provide lighting and minimal support services. Everything else is in the original building section. It is also easy to expand on the other two walls if appropriate.

U-shaped flow has become the most popular building shape over the past 20 years. The reason is that it permits storing the most active products close to both the receiving and shipping docks. Thus, the industrial engineer can minimize travel distance on the items with the largest pallet movements. Also, it tends to group most employees in a small area, simplifying supervision. Overall staffing for the facility is thus minimized.

Increased use of computerized warehouse management systems has improved location and labor control, making U-shaped product paths easy to maintain.

Rectangular. Straight-through materials flow buildings have docks at opposite ends with storage rack aisles parallel to the flow so that an item can move in a straight line from receipt to storage, picking, and shipping. The building width is a function of the number of truck doors needed, which will be on about 12-foot centers. Thus, if 10 doors are needed for shipping, the building may be 120 to 150 feet wide. The long dimension is calculated to provide sufficient area for staging, storage, and operations. Typical ratios are from 1:2 up to 1:5. Expansion of straight-through-flow buildings is on the long side to provide for additions to all the operations roughly in proportion to the original space allocations. Straight-flow buildings have an inherent operating disadvantage: all material must traverse the entire long dimension.

Hybrid. Some warehouses have a large number of quite different activities dictated by product or corporate circumstances. Examples are cool and frozen material storage rooms, unit repacking or packaging functions, hazardous materials items, and so forth. These special circumstances result in buildings that do not meet the general types described. A common hybrid today occurs when the building storage area is designed for very high storage. Stacker cranes can store products 85 or more feet in height and typically require only very narrow aisles 5 feet or less in width. In these cases, unique building specifications may be used to control access and environmental conditions in the storage module.

Warehouse Equipment

Most warehouses use conventional-style equipment for the storage and movement activities. Some conventional items are as follows.

Pallet Racks. These are used to store palletloads of product at multiple levels, making better use of floor space. Figure 10.3.2 shows a typical arrangement. Conceptually, racks are storage structures constructed of formed steel with uprights fitted with movable bars set at appropriate heights to accommodate palletloads. Racks are usually strung in long lines with access aisles between them. A typical arrangement has a module consisting of a row of racks holding 4-foot-deep pallets, an 8- to 12-foot access aisle, and another row of racks. Other types of pallet racks are for double-deep drive-through or storage to store pallets deeper. Finally, racks may be fitted with steel or plywood shelves to accommodate individual cases and small parts.

Storage Bins. Usually of steel, bins are short sections of shelving designed to hold small lots of material. Many configurations are used, including drawers, slotted dividers, differing shelf heights, and reinforcing bars for heavy materials.

Flow Racks. Picking of individual items and small cases from bins or pallet racks may become laborious. For some high-volume operations, flow racks are used. A flow rack is usually a rack 8 to 10 feet wide and as deep or deeper. Slide- or roller-equipped angle frames permit loading a case at the rear of the rack so that it will flow down the lane to the picking face. A few to a dozen cases may be contained in a flow lane. Each rack may be six or eight lanes wide and three to five high—a total capacity of perhaps 20 to 30 different items, each supported by a continuous feed of 10 cases or more. This gives a dense, usable storage pattern to support high-volume order-picking activities. In this arrangement, the picking face presents many more items to the picker per foot of access aisle compared to conventional bin or pallet rack storage. The industrial engineer, however, should observe that flow racks typically require that every case be handled twice: in and out. Thus, the highest-volume items are most often stored in palletloads, not in case flow racks. The best use of case flow racks is for medium-usage items. A related common technique is to use pallet flow racks for items that are very high volume.

Conventional Forklifts. The oldest type of mobile pallet-moving equipment is the four-wheel industrial truck equipped with an elevating mast. Drivers may either sit down, stand, or sometimes walk along, depending on the design. Power may be battery, propane, or gasoline. Conventional forklift equipment is used in a wide array of missions because they can travel great distances, carry loads of up to several tons, maneuver in 12- to 15-foot aisles, and enter highway trailers safely. They are used for large bulk-storage areas where palletloads may be double- or triple-stacked and rows of pallets may be 10 to 15 deep. Thus, a conventional forklift might service blocks of many hundreds of palletloads.

Narrow-Aisle Lift Trucks. The typical narrow-aisle truck has two outriggers to straddle a pallet, providing a noncounterbalanced base on which to operate. The driver usually stands to operate the vehicle. Narrow-aisle vehicles are in wide use, right-angle stacking in 7- to 10-foot aisles, and stacking to heights of 30 feet or more. This gives dense storage patterns, usually based on concepts of random access to any pallet in the storage block. Narrow-aisle equipment usually cannot enter highway trailers, although some special designs with large front caster wheels are available.

Reach Trucks. An important variation of the narrow-aisle straddle truck is the use of special masts and forks that extend mechanically in the direction of travel. This allows the vehicle to stack materials closer together by eliminating the straddle outrigger. Other versions can reach out a full pallet depth to deposit loads in an inside rack. This double-deep storage increases storage density.

Very Narrow-Aisle Trucks. Special vehicles have been designed that can rotate their forks or forks and masts. They are called *swing-reach,* or *turret* trucks. Because they do not have to turn to right-angle stack into a rack, they can operate in aisles only a little wider than the pallet. Aisles of 60 to 72 inches are common. Another characteristic is that the vehicles have to be very large and heavy to accommodate the complex mast equipment. This results in a stable platform from which great pallet elevation heights can be achieved. These classes of equipment can store material safely at 40-foot elevations in aisles under 72 inches wide. The size and tight quarters usually require electronic or mechanical guidance to prevent contact and damage to the rack structure. The industrial engineer using very narrow-aisle trucks should note that these vehicles have long-radius turn requiring an aisle of 15 or more feet at both ends of the rack access aisle. As a result, typical installations have very long storage aisles; 300 or 400 feet with intersections are common.

Stacker Cranes. Stackers are manufactured in a wide range of configurations. Their basic purpose is to operate from the top of a storage stack on rails mounted to the building or rack structure. Heights are essentially limited only by economics, and stack heights of 100 feet or more are reasonably common. Stackers are usually operated by computers, fitting into highly mechanized or automated activities. In these cases, without operators, the building structures may have minimal lighting and heating—only enough to preserve the product's life. Energy savings can be significant.

The industrial engineer who is designing facilities should note that all narrow-aisle equipment such as stackers and very narrow-aisle, swing-reach equipment lose time when changing aisles. Appropriate facility layout, then, usually requires fairly long aisles with few occasions to turn into adjacent aisles. The typical facility is long and narrow—ratios like 5 or 10 to 1 on length and width.

Floor Tractors. These units are used to pull trains of floor trailers over great distances in a warehouse. A frequently accepted rule is that elevating trucks should not travel more than 200 feet from their base. For greater distances, it is more efficient to load a pallet on a trailer and haul multiple loads to the destination. Floor tractors can pull trains of 10 to 12 trailers, each with two or more pallets aboard.

Automatic Guided Vehicles. Essentially, the electric floor tractor can be equipped with computer and sensing devices to permit the vehicle to deliver and pick up goods throughout a warehouse. Installations of 50 to 100 automated guided vehicles (AGVs) operating in multimillion-square-foot buildings are found today. The loading and unloading of the AGV is normally automated, and a master control computer directs the entire flow.

Conveyors. Warehouse conveyors are used to move product within and between operations. The conveyors may be belt, roller, roller with over- or underbelt, skate-wheel powered, or free. Typical applications are combined with flow racks for picking operations or for long-distance movement of pallets or cases from storage, docks, and ancillary operations. Very complex conveyor systems, combined with scanners and reading devices, flow gates and computers, can result in extremely efficient, modern distribution centers.

WORK STANDARDS, INCENTIVES, AND COST CONTROL

Control of productivity in a warehouse presents different problems to the industrial engineer than those encountered in the manufacturing activities. First, warehouse personnel are usually spread sparsely over hundreds of thousands of square feet of floor area. In manufacturing, there is normally a dense, concentrated population. Second, warehouse personnel are mobile—the essence of the operation is rapid physical movement in three dimensions. Finally, the work tends to be diverse and of long cycle, not paced by machinery.

Nevertheless, work standards have been applied in many distribution centers. Penetration is highest in warehouses closely allied with manufacturing facilities.

Standards

Standards are set using all of the same techniques as in manufacturing:

- Stopwatch studies of well-documented, short-cycle activities.
- Elemental standard time data developed within specific industries and for the materials handling function as a whole.
- Higher-level standard data for long-cycle operations have been developed to aid in staffing decisions. These are widely used in industries such as grocery products, in associations like public warehouse groupings, and in government.
- Ratio-delay-type studies to determine the total time spent in a warehouse divided to many functions are widely used as a starting point in developing which activities are large enough to warrant standards. Formal, engineered time standards are used in perhaps 50 percent of all warehouses today.

Incentives

Monetary incentives may be used to improve individual or group performance levels above standard output. Perhaps 25 percent of warehouses have some form of incentive compensation today.

Cost Control

Staffing requirements for warehouses frequently vary through the day, week, month, and season. Variable workloads are a vexing problem. Traditionally, most warehouses were staffed for a reasonably high level of activity—perhaps the 75th percentile. Overtime was used to reach the peaks, and layoffs, make-work, postponable work, and the like were used to reset the workforce in low-volume periods. Recent expansion in the use of computer-based management control techniques and work standards has resulted in much better control of staff levels. Current methods use radio-frequency transmissions of work requirements, feedback loops, standards, and piece counts to control productivity. Part-time employees and interdepartmental transfers for temporary periods have facilitated productivity control.

COMPUTER WAREHOUSE MANAGEMENT SYSTEMS

The most significant improvements in warehouse management in the 1990s have been the development and implementation of product identification, tracking, and control systems; the accurate, rapid identification of products; and the use of this information in controlling the entire warehouse process. These have been key factors in improving productivity and service management. Computers have had the ability to track products and control machining processes for many years. Recent advances in automated identification techniques have improved accuracy. The combination of these three technologies has been a key factor in the development of today's modern warehouse management systems.

The Two Key Elements

A warehouse management system consists of two elements, or subsystems. First, it is necessary to have a technology that can identify the product or entity to be controlled and to transfer it to the computer. This technology is typically purchased, and one can choose from a wide variety of equipment and methods. For the warehouse, scannable bar coding is the current method of choice. The bar code is read, decoded, and sent through a communications system to a computer or controller. In the warehouse, this communication is by radio-frequency (wireless) transmission. Second, the system requires a computer that will interpret the information, update records, and trigger suitable actions (i.e., the tracking and control system). It is very important to recognize that these two systems are quite separate. The industrial engineer can adopt any of a myriad of identification and communication technologies. These decisions are almost wholly distinct from the interrelated decision on the computer processing system that will act on the acquired identification data after it is acquired. The computer processing system can be modified many times in the future, but it will be much harder to change the basic identification technique.

Bar Code Scanning. This is the product identification method in widest use today. A bar code is a group of vertical solid lines that are printed together on a label. The width of the space between the lines can be varied to create a unique code; that is, the width of the spaces and their arrangement can be used to denote a letter, number, or symbol. Figure 10.3.3 shows a typical bar code.

The bar code is read by a scanner that moves a beam of intense light across the label. The light is reflected back by the spaces between the bars, interpreted by decoders into useful information, and transmitted to a computer or controller for receiving and action. Figure 10.3.4 illustrates the reading of the bar code label, decoding, and transmission to a process controller or computer for action.

There is a wide range of scanners available, from handheld to fixed. The scanning technology also is extensive, with at least three different methods in use today:

- *Helium-neon laser.* These have the longest scanning range and fast reading capability, making this method suitable for fixed stations.
- *Laser diode.* Less power, high durability, and longer life expectancy result in this technology being applied in handheld portable scanning installations.

0039391

FIGURE 10.3.3 Typical bar code.

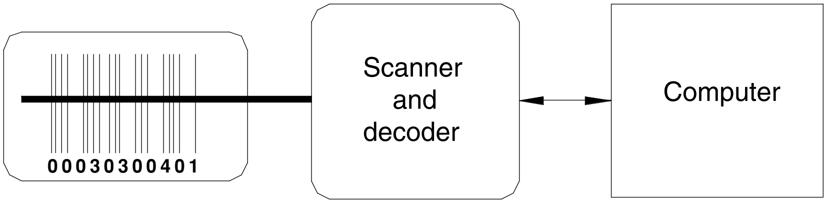

00030300401
Scanner and decoder
Computer

FIGURE 10.3.4 Identification—the key to the system.

- *Infrared.* Low power usage, low cost, and small size are important factors. Infrared can read labels through grease, dirt, and opaque coverings, making the technique particularly useful on the shop floor.

Scanning today can be done at distances as short as an inch to as much as 18 feet. The scanned information in the form of digital signals is transferred by wire or radio-frequency transmission to a decoder. The decoder senses the light intensity, differentiates between the spaces and bars, and assigns an alphanumeric character to the signal. The stream of signals is reduced and interpreted into a data set. This set can then be stored or transmitted, as required by the application.

In the modern distribution center, a range of identification technologies are used to determine the items received from vendors, to maintain accurate stock location systems, to direct order picking, packing, and assembly, and to manifest, route, and control outbound orders. While bar coding is in the widest use, there are many examples of voice recognition, escort memory, optical scanning, and other systems in use. A good example is shown in Fig. 10.3.5.

A modern, automated, order-picking system starts with a scanner to identify the customer order at the workstation. The scanned information signals a computer transmission to turn on lights to direct the order picker's attention to the correct item. A digital display notes the quantity and disposition of the pieces needed.

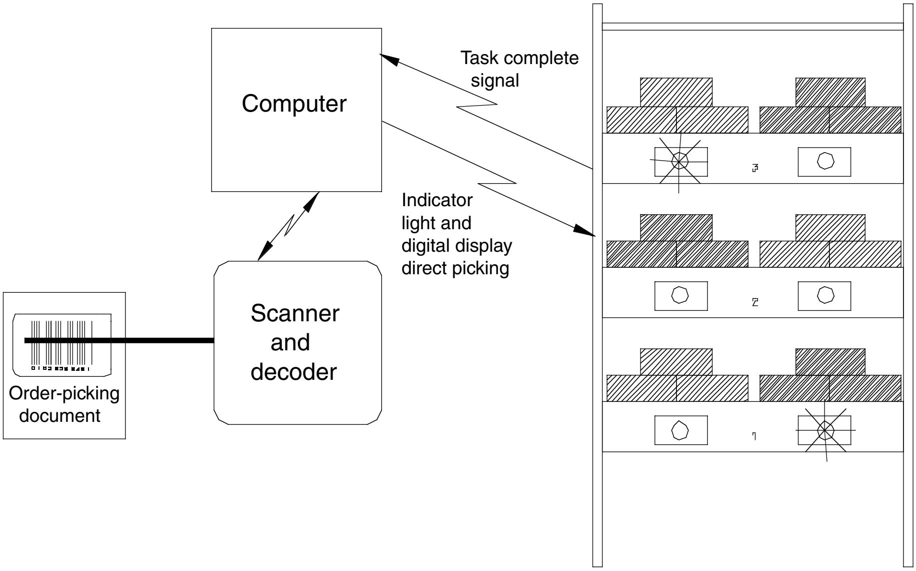

Computer
Task complete signal
Indicator light and digital display direct picking
Scanner and decoder
Order-picking document
3
2
1

FIGURE 10.3.5 Computer-aided picking.

Product Tracking. Product tracking is a logical development that stems from the combining of product identification technology with the extensive record-keeping, analytical, and data processing capabilities of electronic computers. Basically, a product or a work order can be accurately identified when it arrives at a workstation. This information is then transferred automatically to a computer that records the arrival and adjusts related records to reflect the information. A product-tracking software program then can process and utilize this information for a wide range of applications. Of primary interest are tracking systems in manufacturing, distribution, and freight transportation.

Application in Warehousing and Transportation

Product identification, tracking, and control systems have been widely applied in warehousing and transportation systems. Modern warehouses typically store thousands of different items and deal with hundreds or thousands of individual receipts and shipments in the course of a business day. Keeping track of orders, materials, and personnel in the modern distribution center is a complex activity. Bar coding is the most-used identification technique. The information scanned is transmitted to a tracking software program that can transmit control information and instructions back to the data terminal. Figure 10.3.6 illustrates how product identification combined with a computer control system is used to control material flow in a modern distribution center.

Typically, materials shipped to a facility are labeled by their manufacturer with bar coded or other data. The data includes company, purchase or work order number, product name and number, quantity, and so forth. At the receiving dock, the label is read by a fixed or handheld scanner.

The scanned data is verified by a blind count entered by the receiving operator. Both sets of data are used to access the computer records of purchase orders and related information. After verification, the computer directs the disposition of the materials received. Normally, this is done by automatic printing of an internal routing and identification tag or label that is put on the material. The printing is controlled by the tracking computer. Typically, the palletized load with its label is then picked up either automatically by a computer-guided vehicle or by a manually operated forklift truck. Again, the vehicle will have been scheduled or controlled by the tracking program. Communication with the AGV or the forklift will be by RF transmission.

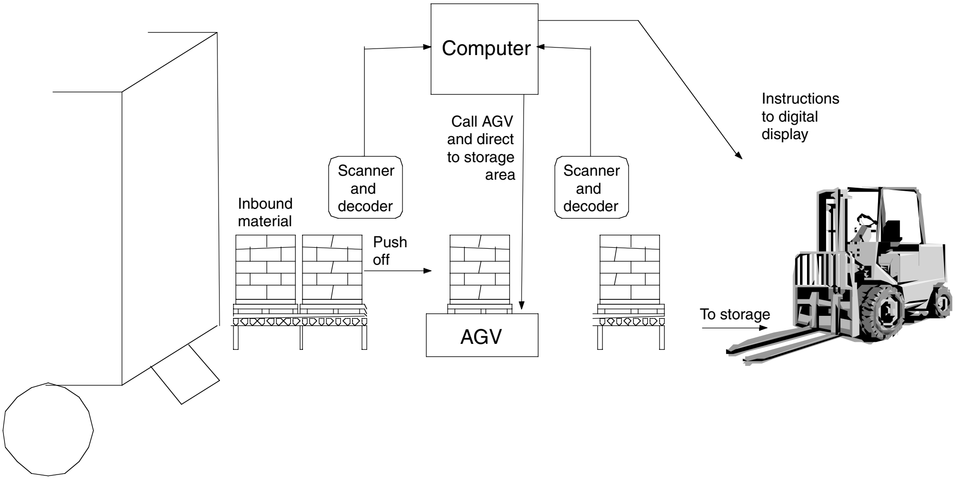


FIGURE 10.3.6 How product identification is used to control movement.

WAREHOUSE MANAGEMENT

The computer will select the storage or assembly line location to which the material is to be delivered and direct the vehicle and its movement. When the product arrives at the designated location, the operator scans both the routing label and the identifying label at the destination storage location or workstation. This is verified by the computer, and the status information is adjusted in the computer file.

Following the completion of the storage or picking in the warehouse, the material, operator, and status are scanned and/or key-entered to continue the tracking process. Step by step, the computer can direct operations, select delivery locations, call and direct automatic and manually driven materials handling equipment, and record status. The final operations typically involve order picking, assembly, and loading of completed customer shipping orders onto transportation carriers. Figure 10.3.7 illustrates how a fixed vertical scanner identifies an outbound order, combines this information with automated weight data from in-line scales, prints truck manifests, and sets conveyor gates to direct the order into the right truck.

The materials are then handed off into the next tracking system. All of this depends on the existence of a product identification technology, RF and wire transmission, and a computer tracking and status software/hardware package. The assembly of these different technologies into a single coordinated flow and system are key elements in modern warehouse management systems.

To illustrate, a very large central distribution center operated by a major U.S. manufacturer uses bar codes, scanners, and process control computers to manage the entire materials handling and product flow in a 2-million-square-foot distribution center. The process will be described subsequently. Similar processes are operated by perhaps 25 percent of all distribution centers today. The industrial engineer needs to understand these applications.

Receiving. Materials are received in palletloads containing one or more items. Each pallet or case of an item has a manufacturing ticket identifying the number of cases of each item, the quantity, the date, and the time. The pallet is removed from the delivery truck and deposited on an output conveyor after adjusting quantity, load size, and so on to make sure it fits the physical warehouse system. The manufacturing ticket is wanded, variable data entered, and a put-away ticket is automatically produced showing the assigned location and the quantity to be stored. The computer then calls an automatic guided vehicle to pick up the palletload. It

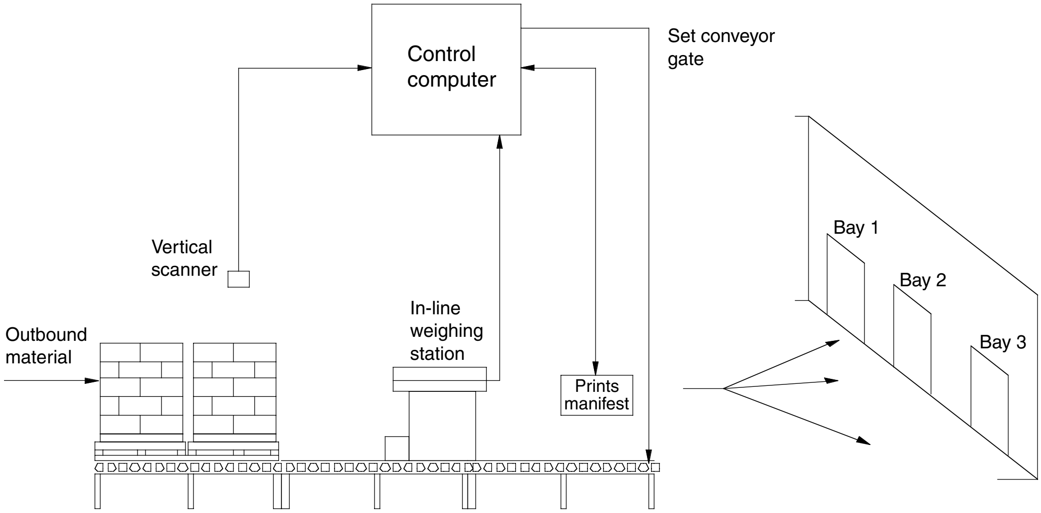


FIGURE 10.3.7 Elementary identification operations.

automatically delivers the pallet (either full or part) to the storing location receiving conveyor. The warehouse management system next assigns a forklift truck to pull the pallet and deposit it in its designated location. The forklift operator wands the put-away ticket and a bar code label at the rack location. The computer receives and verifies the transaction and then updates the inventory record for the storage location.

Order Picking and Assembly. The warehouse process control computer receives shipping orders from the company mainframe computer. The processor then determines which items are needed from each storage zone in the warehouse. The local zone forklift truck operators receive information by radio frequency displaying the next location and item to pick. The operator selects the correct number of cases, wands their bar code, and moves the product to an outbound conveyor. The process controller can verify the picked item identification and quantity and can signal necessary corrections. The controller then calls an automated guided vehicle to pick up the pallet of material and move it to shipping.

Shipping. On arrival at the shipping dock, the AGV deposits the pallet on a feed conveyor. Dock handlers scan the item/pallet, the computer signals the appropriate truckline, and the handler removes the pallet from conveyor and drops it on the proper floor lane designated for the truckline. Priority, must-ship items are dropped close to the door. Multiple pallet orders are marshaled in the truckline drop spots, because part of an order can come from many locations in the distribution center. The shipping team leader calls in trailers and arranges for loading. The loader enters data into a computer at the dock face desk terminal, then wands each pallet as it is loaded into the truck. This relieves the dock area inventory in the warehouse computer.

Thus, the product is tracked at every stage of movement through the facility. At any time, management personnel can inquire to determine the status of any item or order. Exactly the same system can be used in each stage of the manufacture, warehousing, and delivery of materials. All depends on the product identification technology.

PLANNING THE DISTRIBUTION CENTER

Given that a company either has or intends to set up a distribution center, the design project will require a high level of detailed information and data. The following outlines the design process that is typically followed by the industrial engineer.

Determine Functions to Be Included

What functions will be contained in the warehouse? This can be a very long, complex list of activities:

- Receiving, counting, verifying, and accepting inbound materials and finished product
- Transporting and storing the products in appropriate storage locations and equipment
- Maintaining a control system to locate all materials and paperwork within the facility
- Receiving and handling shipping orders
- Picking, packing, and assembling outbound materials and marking them for accurate delivery
- Routing outbound goods by carrier, calling the carrier, and staging and loading onto the outbound vehicle
- Checking outbound materials for accuracy and adjusting internal stock records

Determine Initial Space Allocations

Preliminary estimates are frequently made to determine the total space needed and to allocate it to the listed functions. This is called a *block layout.* At this stage, provision is made for utilities and support services, offices, staging areas, and so forth to estimate the building dimensions to a reasonable accuracy level.

Develop Data on Volumes and Flows

There are five basic types of data needed:

Inventory

How many items will be stored
What quantities are expected for each item
The item dimensions and storage characteristics
Activity (receipts, picks, and turnover) by item
Forecast of growth of the items or item groups and of new items expected
Nature of the items (fragile, hazardous, liquid, etc.)
Number of cases, pounds, and pallets or other units to be stored
Normal ratios of items per case, cases per pallet, pallets per truck, weight per pallet

Receipts

Number per time period
Lot sizes
Need to segregate lots of an item
Seasonality

Shipping Orders

Number by time period
Seasonality
Types of orders
Characteristics (items per order, lots per item, orders per shipment, etc.)

Order Analysis

Line items per order
Pieces
Cartons
Frequency distributions of pertinent data

Service Requirements

Timeliness in shipment
Accuracy requirements
Special markings
Promotional and regular materials

Observe Operations

The industrial engineer has to be knowledgeable about current warehouse methods in the existing facilities, aided by regular observation of each function performed, flowcharts, information about current work standards, and lists of questionable practices. The results of this work are normally discussed with operating managers to ensure a full understanding of the current operation—its performance and requirements, special conditions, and problem areas that need to be addressed.

Establish Alternative Methods and Equipment

In any warehousing function, there are a number of ways in which the work can be done. A new facility may have been accepted because more space is needed for expansion, or it may provide the room and the environment for major productivity or service improvement given the following conditions:

- That the job to be done has been described
- That the current problems and opportunities have been isolated
- That the current methods have been identified
- That objectives for improvement have been established

The industrial engineer then has to describe a number of feasible alternative plans. The different plans usually involve an increasing level of mechanization or automation. Higher levels frequently have a high capital expense, but they may have low operating labor cost. Higher stacking, for example, uses less floor space, but requires more-expensive equipment.

Create the Preliminary Design

The typical design study is done in two steps:

- Individual operations are examined—for example, how high to stack. General answers are reached for each activity (picking, order assembly, storage, etc.).
- These preliminary designs for each activity are aggregated to describe several feasible building layouts using one or more of the warehouse design methods described earlier in this chapter.

Evaluate the Alternative Designs

These are evaluated for the following:

- Feasibility and applicability to the facility mission
- Operating cost
- Investment requirement
- Maintenance
- Flexibility to suit changing needs in the future
- Risk involved in achieving the desired results and savings
- Implementation time

All of this information is then evaluated using traditional industrial engineering cost techniques, such as discounted cash flow and its variations. A decision can then be made regarding the best alternative for the circumstances evaluated.

Prepare Detail Designs

Following acceptance of the basic facility conceptual design, a much more detailed plan needs to be prepared. This plan usually involves the following:

- Contact with equipment vendors for additional ideas and constraints in the functional areas.
- More detailed data in some areas to support elements of the design. For example, how many packing stations are needed? What conveyor speeds are most effective? How are the various lines staffed at different volume levels?
- Simulation—modern computer simulation methods yield sound, operationally correct answers to many detail design questions. In particular, conveyor systems and staffing levels are sensitive to short-cycle volume and product mix shifts. A simulation of the system in operation is a sound investment in achieving a problem-free facility start-up. The simulation can later be used for operator and supervisory training.

Prepare Written Recommendations

At the conclusion of the design process, it is normal to prepare a complete written report on the project. The report may be needed to get internal or external financing. On another level, it should serve as an operating manual for the managers of the warehouse operation. The report typically includes the following:

Equipment specifications. Sketches, catalogs, prices, special requirements, numbers of units, and operating speeds and conditions.

Staffing. The number of people needed at each function for varying volume levels should be specified. This can include job descriptions and reporting relationships.

Operating narrative. A written description of how the facility functions. The narrative starts at receiving and traces the entire material flow, including storage and put-away, order picking, packing and assembly, and shipment loading.

Facility layout. The floor plan for fixed equipment showing all operating areas, staging, utilities, support functions, and offices.

Work standards. Each repetitive job should have a standard that can be applied to measure and control productivity and to establish the building's staff requirement.

Economic feasibility. The initial budget level costs for construction, equipment, staffing, and implementation need to be refined. The final report should then present the economic and operational basis for approval of the warehouse investment.

CONCLUSIONS AND FUTURE TRENDS

The design of distribution centers has changed markedly during the last decade. The principal reason was a significant shift in the typical warehouse mission. Formerly, the major activities were the receipt and storage of finished goods and the filling of customer orders to replenish warehouses and retail stores.

Increasingly, customers demand that significant value-added services be provided by their manufacturing sources. Some of these added services may require reconfiguring, remarking, and repackaging of finished products. Because distribution centers are frequently far from the manufacturing plant, the new services often are assigned to the distribution system for completion. This trend has generated major new activities in the distribution center, resulting in somewhat higher warehousing costs and more-complex operations. The ability to cope with these customer demands smoothly, quickly, and without excessive cost increases is a challenge for the industrial engineer. Success can result in improved competitiveness and market leadership for the manufacturer's products. Failure can mean lost customers and lost market share.

There are two other important trends in warehousing that the industrial engineer should understand. First, the total number of warehouses operated by a company tends to decline over time. The reason is the drive to achieve economies of scale through larger, more-mechanized, and increasingly efficient buildings. In many ways, this consolidation of operations is a direct result of the increased complexity of the newer value-added activities. It is easier to design and install new operations and equipment in one or two locations than it is in many.

The other trend has been a significant growth in the use of third-party logistics providers. Many companies have chosen to engage specialist companies to handle their logistics—presumably because these experts can do the job cheaper and better. However, third-party operations still represent a rather small percentage of the total warehousing function in business. Corporate-run warehouses are still the standard in most industries.

To summarize, warehousing today is a complex, relatively costly activity. The industrial engineer operating in this field has the opportunity to significantly improve the warehouse function and to increase the product's market competitiveness.

FURTHER READING

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BIOGRAPHY

Herbert W. Davis is founder and chairman of Herbert W. Davis and Company, Management Consultants, Fort Lee, New Jersey. He has been a materials handling and logistics consultant since 1958. During this period, he completed over 1000 assignments for 300 corporations in North America and Europe. Davis holds a B.S. degree in mechanical engineering and an M.S. in industrial engineering from Stevens Institute of Technology. He serves on the Board of Executive Advisors of C. W. Post College of Management and is a former director of the Council of Consulting Organizations and its predecessor, ACME. He is a Certified Management Consultant (CMC) and a founding member of the Institute of Management Consultants. He has been a contributing author to *The Distribution Management Handbook* (1994) and *Maynard's Industrial Engineering Handbook* (1992).

CHAPTER 10.4

DISTRIBUTION SYSTEMS

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During the first half of the twentieth century, industrial engineering practice tended to concentrate on the manufacturing process—a process costing on average about one-half the selling price of the goods.

Since 1950, however, industrial engineering techniques have played an increasing role in the nonmanufacturing segment of this total cost framework—essentially, the logistics activities encountered in the delivery of products to the manufacturer's customer. The customer may be another company or plant, a wholesale distributor, a retailer, or a consumer. Industrial engineers have played a major role in the development of the distribution function and the design, operation, and control of distribution systems.

A corporation's distribution system has become increasingly complex as companies have expanded product lines and increased the number of sales channels in which their products are sold. Each channel has tended to develop a unique set of service requirements that define the competitive environment, the logistics capability required, and the cost for participating in the channel.

The modern distribution system has to supply each of the company's sales channels with exactly the right services demanded by the customers in each channel while at the same time containing costs at internally acceptable levels. The design and operation of the corporation's distribution system requires a high level of industrial engineering practice. The system itself is dependent on complex machinery, well-trained and disciplined workforces, and a high level of data manipulation and management.

This chapter describes the development and current practice in distribution system design and operations, written from the vantage point of the industrial engineer.

ROLE OF THE DISTRIBUTION SYSTEM

Prior to World War II, most manufacturing was done at plants assigned one of the following roles:

Geographic role. To serve a territory that might be the world, the United States, or a smaller geographic region. Location was a function of the economies of raw material availability, transport cost, and the market area served.

Product role. A plant produced a specific product line that was the company's entire output or portion thereof.

In this environment, product could be shipped directly from the plant of manufacture to the customer. In large segments of business, however, plants were distant from customers, and reasonable, timely delivery service required some intermediate storage warehouse closer to the customer. These field warehouses were the forerunners of the modern distribution center and network, with its computer control systems and sophisticated product flows.

In the 1950s, a company with a high-volume, nationwide sales pattern might have had 100 or more warehouses, had product supplied by one or more product-line-specialized facilities, and used water or rail transportation for the primary (plant to distribution warehouse) leg. Secondary transport, usually local drayage to the customer, was done by motor truck. Two things changed this pattern:

1. World War II saw the emergence of modern concepts of logistics analysis, materials handling systems and equipment, and mechanisms to time and control the total material flow.
2. The National Defense Highway System was authorized in the early 1950s, and it evolved by the 1960s into an extensive, easy-to-use national express highway network. This led to the growth and importance of major national highway motor carriers able to compete in price with the older water and rail systems and to offer better, faster service.

These changes took place within the framework of important developments in the corporate sales and marketing function. Product diversity, reasonably prompt, complete delivery, and national pricing and promotional practices led to an explosion in the number and variety of products and styles offered to customers. Offering these more sophisticated lines in an efficient manner led to the development of the modern distribution system based on decentralized, standalone, regional warehouses tied together by an information and transportation system. Thus, by the mid-1960s, business had the need for sophisticated distribution systems, the conceptual physical designs, the materials handling technology, and the transport system to make it work.

By the mid-1990s, that physical distribution system had become the major link between the manufacturing plant, the customer, and the marketing/sales function. Current distribution systems are complicated, use a very high level of information and materials handling technology, and are a major operational area for industrial engineering.

DEFINITION OF PHYSICAL DISTRIBUTION

Physical distribution is the group of activities concerned with the control, movement, and storage of materials. These activities may take place within a single manufacturing facility or be played on a worldwide stage. The scope may include activities that occur prior to, during, or after the manufacturing process. In some companies, physical distribution includes purchasing of finished and raw materials, inbound transportation, plantwide storage and materials handling, shipping, and outbound transportation.

During the past decade, physical distribution has come to be considered primarily as the functions that occur after the manufacturing process—serving as the link between the manufacturing plant and the customer. Its assigned functions tend to be the physical, or product-oriented, aspects of marketing. Industrial engineering techniques have wide application in analyzing and improving all aspects of this physical process.

FUNCTIONS INCLUDED IN DISTRIBUTION

The physical distribution system used to control, move, and store products on the path from the manufacturing line to the customer is complex. A typical system has manufacturing plants, which may produce all or some of the product line, warehouses that are supplied products by the plants, and customers who are supplied by any of the plants or warehouses.

Note that the physical facilities (plants and warehouses) are connected by transportation links. Orders for the plants and warehouses come into the system from the sales department through customer service and are directed to the plants or distribution centers for order fulfillment. Inventories are usually controlled by an administrative function that may be responsible also for the system design and control.

Typically, there are five major functions assigned to physical distribution to manage:

1. *Order entry and customer service*
    - Receive orders from customers and sales by telephone, fax, electronic data interchange, Internet, e-mail, regular mail, or hand delivery.
    - Enter and/or edit the information, usually in a computer system.
    - Apply pricing.
    - Select shipping point and transfer information for picking, packing, and transport.
    - Track order and product status.
    - Report status to sales and customers.
    - Answer customer and sales inquiries on status.
    - Solve problems relating to these activities.
2. *Warehousing*
    - Receive materials from vendors, plants, and other facilities.
    - Verify material input and resolve discrepancies.
    - Place materials into storage awaiting instructions.
    - Manage the physical quantities on hand.
    - Pick and pack materials for outgoing orders to customers or other warehouses.
3. *Transportation*
    - Route, rate, and control the use of freight carriers.
    - Transport goods from the plant or vendors to distribution centers and redistribute between multiple centers.
    - Transport goods from distribution centers and plants to customers.
    - Manage many different transportation modes used, including rail, motor truck, barge, ship, and aircraft.
    - Prepare shipments with sizes that may range from small parcels through containers or truckloads up to full bulk shiploads.
    - Receive, audit, and arrange payment for outside, for-hire carriers.
    - Manage the company truck, rail, air, and water fleets.
4. *Inventory management*
    - Determine how much material is needed to achieve the desired inventory turnover, customer service, and cost objectives.
    - Order materials from vendors, plants, and warehouses.
    - Track materials flow and status.
    - Consider the cost to carry inventory, customer satisfaction, and warehouse/plant capacities in deciding when and how much material to order.
5. *Distribution administration*
    - Determine and allocate funds and resources to the various distribution activities.
    - Design and manage the functional activities assigned to distribution.
    - Develop and manage the appropriate control systems.

DISTRIBUTION COSTS

Physical distribution is one of the largest costs incurred in the manufacture and sale of merchandise. Costs have tended to rise over the years when measured by product units (cases, pieces, or weight). The following have been important factors in this cost increase:

- A long-term decline in unit weight corresponding to the substitution of plastics and electronics for structural metals and mechanical controls and the proliferation of protective and decorative packaging material
- An increase in the number of different items offered to the customer, resulting in the distribution of fewer pieces per catalog number
- Refined inventory control and purchasing practices so that customers purchase fewer pieces spread over more frequent ordering patterns
- Value-added services such as preticketing, order assembly by store rather than retailer warehouse, special customer packaging, and so forth.

When measured as a cost-to-sales ratio, however, distribution costs have been cyclical. Costs respond to a large number of external influences such as energy rates, service levels, interest rates, transportation costs and tariffs, competitive pricing, and company policies. Currently, distribution costs average about 8 percent of a manufacturer's sales revenue. The cost pattern from 1961 to 1997 is shown in Fig. 10.4.1. Figure 10.4.2 shows the change since 1980 of the three largest cost elements: transportation, warehousing, and inventory.

Long-Term Trends

There have been four significantly different periods resulting from external changes in the business environment in which distribution operates. As a result, distribution costs have exhibited the following pattern.

1962 to 1973. In the United States, this was a period of steady growth marked by heavy price inflation from 1969 onward. It was the period of American economic dominance. U.S. companies' operations in Europe alone constituted the third-largest world economy. In dis-

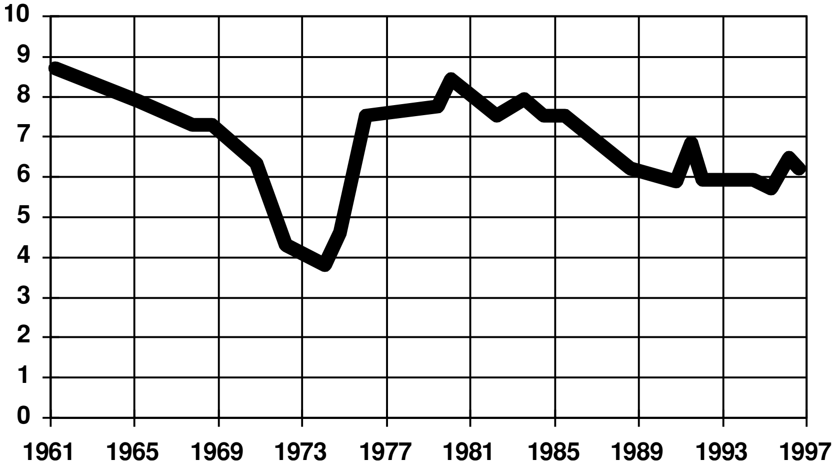


FIGURE 10.4.1 Distribution cost as a percent of sales.

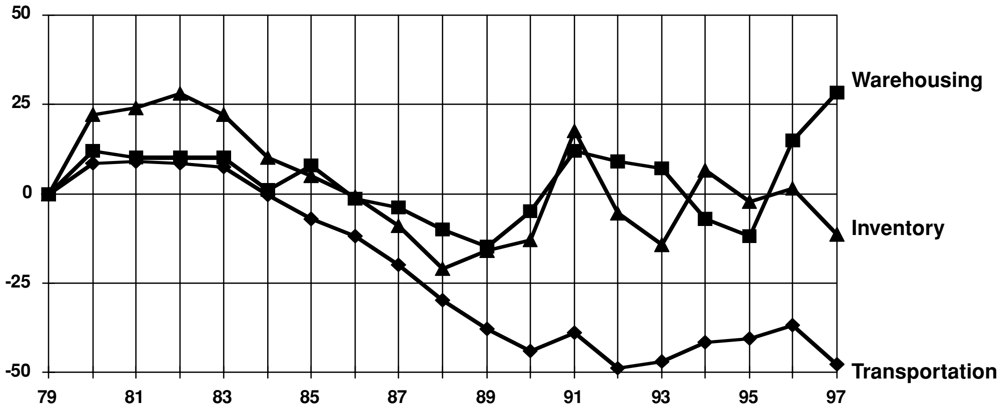


FIGURE 10.4.2 Annual percent cost change.

tribution, it was the period when companies adopted the distribution concept. Consolidated authority over the entire distribution budget resulted in the ability to employ better-trained personnel supported by improved information systems. Distribution cost declined steadily from 10 percent in 1963 to a 1973 level of 5.5 percent of sales, a striking testimony to the power of the physical distribution concept.

1973 to 1980. The oil embargo ended the first distribution era. This second period was one characterized by the energy crunch, inflation, declining productivity, and a growing foreign presence in the domestic U.S. markets. Preoccupation with cost containment pushed many companies into ignoring product quality and customer service issues. All of the gains of the 1963 to 1973 era were lost, and costs once again hit 10 percent of sales by the end of the 1970s.

1980 to 1990. This period started with transportation deregulation as an attempt to deal with costs through market forces rather than government regulation. The most important external factors in the period were the decisive changes wrought by corporations in dealing with foreign competition, inflation, and productivity. This era was the time of corporate restructuring, offshore sourcing, manufacturing consolidation, capacity reductions, and centralization of major activities. It was a period of sustained, profitable growth in the domestic economy. In distribution, there was a new emphasis on productivity, a drive for customer service and quality excellence, and much better computer support. The result was a significant and steady reduction in all of the major distribution costs to a level of about 7 percent of sales.

1990 to the Present. Since 1990, total distribution costs have been reasonably steady. Major cost-reduction efforts led by industrial engineering teams have substantially improved internal productivity. However, the growth of value-added services in the expanded and more-complex supply chains have largely negated internal cost reductions. The result: costs have been level to slightly higher. By 1998, total distribution costs for manufacturers had reached an average of 8 percent.

Why Costs Vary

The major factors that cause costs to vary from the average are as follows.

Product Physical and Channel Differences. Product distribution cost as a percent of sales has a strong, central tendency across a broad range of products.

The reasons for cost similarity are the relative importance of common underlying factors like freight tariffs, interest on capital invested, wage rates, building rents, and energy. Because of this, many companies tend to compare their product distribution costs only to their direct competitors. Doing so, however, can miss major opportunities to learn from other industries. Many distribution activities are similar across industries, (e.g., order entry, truck loading, case picking). Thus, it is important to study advances made outside a company's narrow list of competitors. A high level of industrial engineering effort in internal cost reduction and productivity improvement can lead to world-class performance in distribution.

Product Value. There is an important inverse relationship of distribution cost with product value per unit weight, as shown in Fig. 10.4.3. Small and lightweight products of high value (e.g., jewelry, pharmaceuticals, electronics) tend to have low freight costs compared to bulky, heavy materials (e.g., foods, machinery, consumer appliances). This advantage is partly offset by larger, more-expensive inventories and by costly order-handling procedures associated with high-value products.

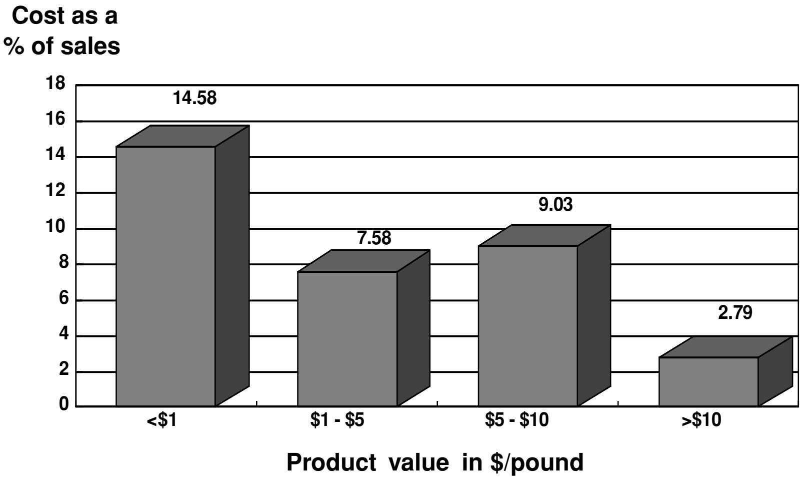


FIGURE 10.4.3 Product value.

Company Size. Size is a complicated factor. Many large companies have higher wage rates than small businesses. However, very large shippers have stronger negotiating leverage when dealing with carriers and other suppliers. This tends to reduce freight and material costs. Figure 10.4.4 shows that costs tend to be similar except for the two extremes of company size—very large and very small.

Finally, a most interesting aspect of distribution cost is the similarity of total cost despite differences between products, companies, and geographical location. Probably this results from the almost universal application of common industrial engineering techniques. The industrial engineer can directly influence distribution costs by revising material flows, by reducing the number of shipping and handling moves, and by installing modern equipment and computer controls.

EVOLUTION OF THE MODERN INTEGRATED LOGISTICS SYSTEM

During the 1990s, there has been a growing interest in multicompany integrated supply chains. The distribution systems operated within a single company have become more complex. A manufacturer, for example, may operate simultaneously several, quite different, systems.

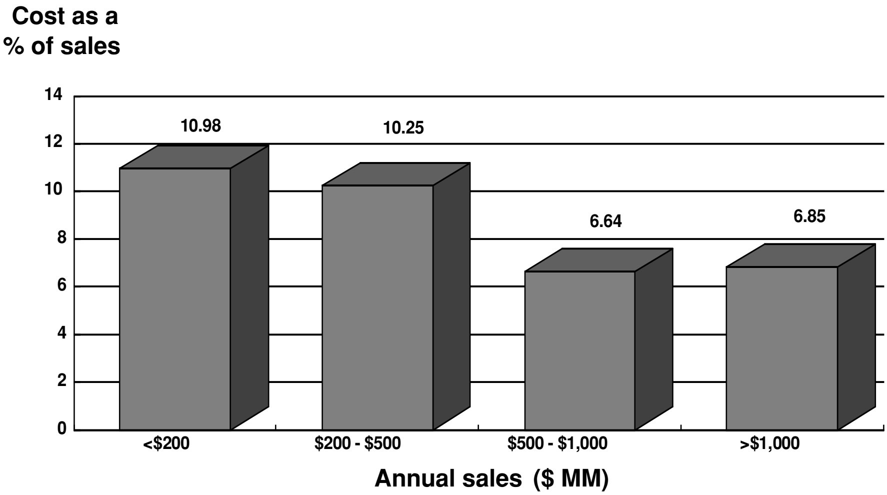


FIGURE 10.4.4 Company size.

Plant Direct to Customer

Many large retail chains and mass merchandisers have set up regional collection or consolidation points for products purchased from their suppliers. These manufacturing suppliers typically ship relatively large quantities directly to the retailer's consolidation point—usually a third-party warehousing or freight company. At the consolidation point, the freight from many vendors is sorted to each of the retailer's warehouses or stores. The consolidated freight is then forwarded to its destination. The consolidator may offer a variety of other sorting, segregating, or order assembly functions as it redirects the supplier's order to the retailer's facilities.

There are many other variations of plant-direct shipments. The manufacturer may fill large orders for relatively few items and ship them directly from the manufacturing plant to the retailer's warehouse or even the store. Further, the manufacturer may consolidate product for several customers onto a single highway truck. This truck may then make several drops to the individual customer locations and to the retailer's consolidation points.

A Network of Regional Distribution Centers

These distribution centers are typically assigned responsibility for filling customer orders within a regional territory. In the 1990s, these regional facilities frequently served only a selected group of customers—those with very short time cycle requirements. Historically, the normal region was a 5- to 10-state area throughout which a 48-hour truck delivery requirement could be achieved. Differentiation of customers by time cycle requirement in the 1990s resulted in establishment of same-day delivery regions as small as a single metropolitan area.

Air Freight Distribution Systems

Since the 1960s, most manufacturers have used some air freight to supply customers where the normal supply system fails. However, some high-value product groups, such as pharmaceuticals, electronics, and renewal parts, are distributed by single-shipping-point air freight systems, primarily because the inventory carrying cost for multiple warehouse systems is high and can be dramatically reduced by the use of high-speed delivery.

Ocean Container Systems

Many manufacturers produce products and product lines globally. For example, a large multinational corporation may have factories in Asia, Europe, and North and South America. Typically, high-speed container ships are used to transfer products between the continents. Containers are directed to consolidation and distribution centers, much as is done by truck transport within the United States.

Hybrid Plant-Direct, Regional Distribution Center, and Air Systems

A combination of the four preceding systems has become commonplace. Plants, through use of high-speed, long-distance truck transport systems, are able to supply large retail and commercial accounts directly by use of full and pooled trucks. These systems offer three- to five-day total order cycle times. Then the same manufacturer may overlay a group of small regional stocking warehouses that supply some, usually smaller, customers with same- and next-day service. Air and ocean systems are integrated with these to complete the current hybrid system.

The development of these effective, relatively low-cost hybrid distribution systems depends on modern information technologies that facilitate the smooth flow of data up and down the multicompany supply chain.

DISTRIBUTION SYSTEM DESIGN

The most basic function of the physical distribution system is to efficiently and effectively move merchandise from the end of the production line to the consumer. This flow frequently involves a number of independent companies: manufacturer, wholesale distributor, retailer, and the like. These channels of distribution are usually specified by the marketing organization, and their use is built into the basic organizational and material fabric of the company.

For the industrial engineer, therefore, the important segments of the distribution system are those under the direct control of the manufacturer. These channels are different for different products. There is a major difference between consumer and industrial products and durable versus nondurable goods.

Despite the complexity, however, there has developed a body of knowledge governing the design of an efficient product distribution system. The mission of the system is to deliver product to the customer when the customer wants it, in the proper product mix, and at a reasonable cost. The design of a system, then, includes consideration of cost and service. The costs evaluated usually consist of primary and secondary freight, warehousing expense, inventory carrying cost, and the expenses related to booking and processing the order. The key service factors are prompt and complete fulfillment of the customer order and a high level of information interchange within the entire multicompany supply chain.

System Modeling

The essence of the design problem involves meeting a prescribed set of customer service requirements, like delivery of a complete order within a specific time frame, while simultaneously minimizing the distribution costs for freight, warehousing, and inventory. All of this needs to be done within the physical-capacity constraints of the facilities involved.

This physical distribution system design is done most often using one or another of a competitive group of logistics models. It is seldom worthwhile to develop single-purpose models for a company. Such models are very costly. To reduce model costs, the complex distribution system sometimes is oversimplified, and the model does not use the best technology available.

Three Basic Databases Needed

All models used in distribution network design use at minimum three separate databases. A brief discussion of each follows.

Sales Model. This involves defining volumes delivered by product group and by shipment size to each geographic market area. A universal geographic coding system is used, frequently the postal ZIP code because the code is usually available in the customer account file. The products are grouped by product line, and customer orders are entered showing volumes by line and shipment size.

Shipping Point Model. This involves describing the materials flow and defining the costs for storage and handling at each facility considered. This is an important area for industrial engineering analysis, as the best results will be attained if the costs are carefully developed. Simple accounting-type allocations can lead to errors in the model output. It is important for the industrial engineer to consider a significant number of potential new warehouse or plant locations, well beyond the company's current system configuration.

Transportation Cost Model. A table of freight costs between all locations considered in the model is used to cost different ways of meeting the sales demand. This area requires considerable experience with the transportation system rate structure, the highway and rail networks, and the availability of transportation capacity at the shipping points tested. Basically, the transportation cost model contains freight tariffs for all of the feasible transport methods and shipping points between all plants, warehouses, and customers.

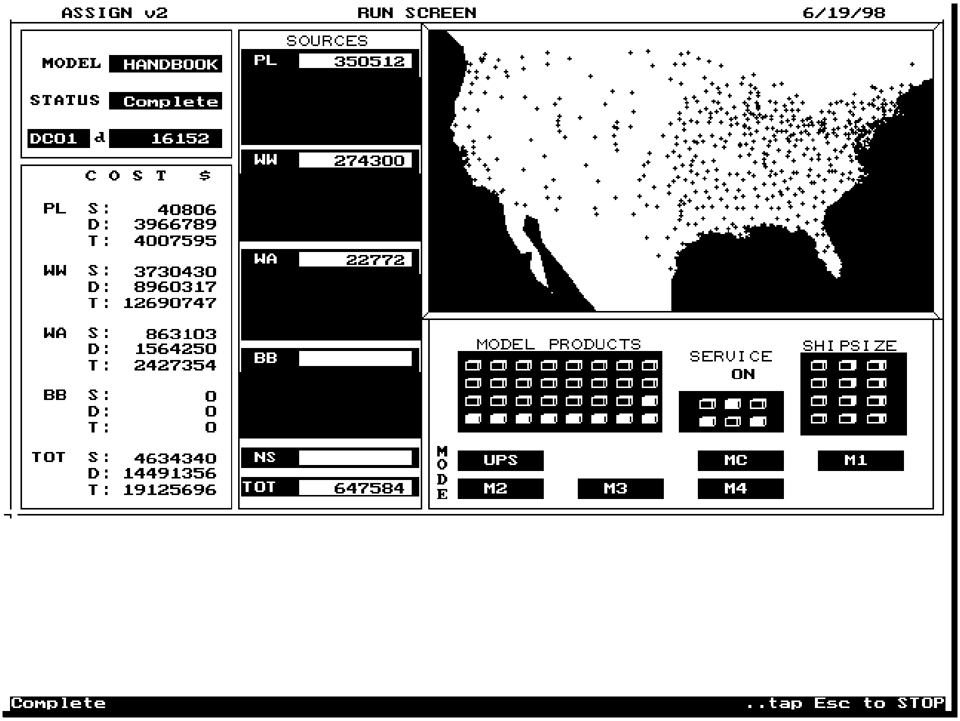
Modeling Strategy

Typical modeling practice is to run a series of tests of the data to validate the model, then to find the appropriate solution. This solution should be developed within the framework of economic justification, customer service requirements, and capacity constraints. For example, some customer orders could be filled at relatively low cost from manufacturing plants direct, such as for full truckloads with adequate lead time. Other, less-than-truckload and parcel orders might best be shipped from a regional or local distribution center. Multiple orders to a local area could be consolidated and shipped as a truckload for cross-docking and local delivery.

Analysis

Commercially available models normally have an extensive set of graphic outputs to aid in analysis of the results and, if necessary, in specifying further runs. Figure 10.4.5 shows some typical output graphics.

Finally, pushpin-type graphic displays are available to help the analyst in all stages of the distribution system design. Such a display, shown in Fig. 10.4.6, is useful in visualizing the largest and most important market areas—areas where warehouses might be indicated. Warehouses are frequently put in large market areas.



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STATUS  Complete         PL   350512
DC01 d  16152            WW   274300
                         WA    22772
     C O S T   $         BB
PL   S:     40806        NS
     D:   3966789        TOT  647584
     T:   4007595
WW   S:   3730430
     D:   8960317
     T:  12690747
WA   S:    863103
     D:   1564250
     T:   2427354
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TOT  S:   4634340
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FIGURE 10.4.5 Model output graphics.

TRANSPORTATION SYSTEMS

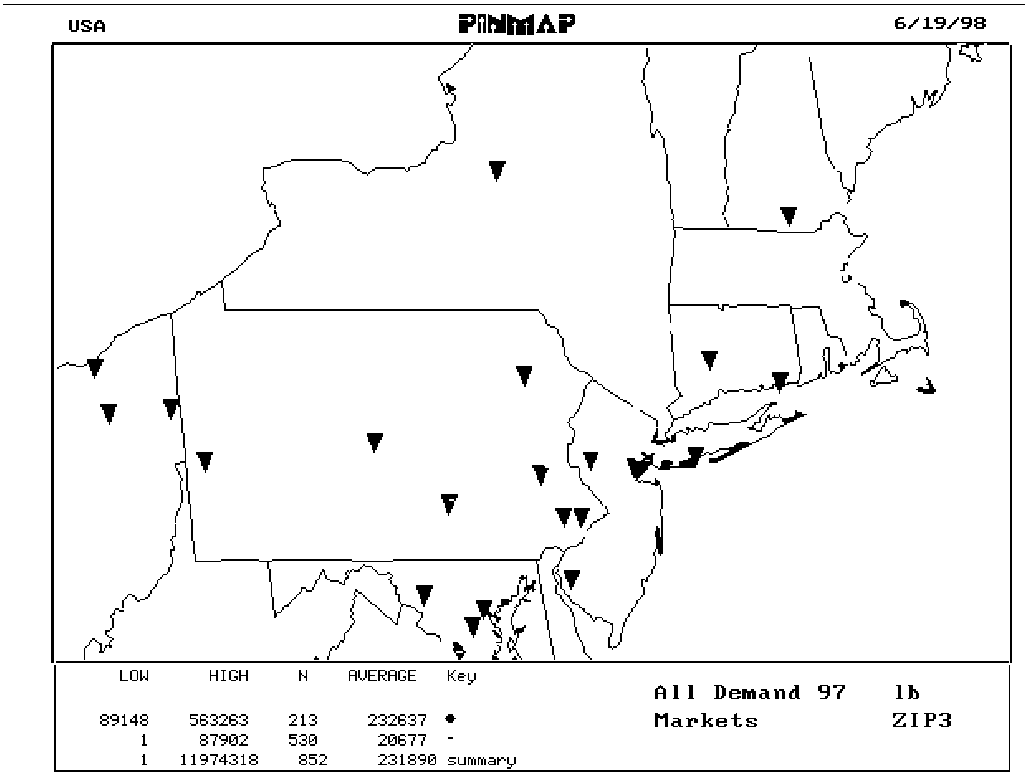
Transportation is the largest single cost in distribution today. It is almost a completely separate function within distribution, because control of cost requires very detailed knowledge of both the alternative modes available and the factors that drive the costs within each. Many of these factors are typical of industrial engineering practice. Others are not because costs are driven by regulatory and technological differences.

Modes

There are many modes of transportation used in product distribution today. The principal modes are as follows:

- Motor carriers (national, regional, and local)
  Less-truckload (LTL) and truckload (TL) carriers
  Local delivery
  Contract truckers
  Specialized commodity carriers
  Private carriage

DISTRIBUTION SYSTEMS



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89148	563263	213	232637	●
1	87902	530	20677	-
1	11974318	852	231890	summary

FIGURE 10.4.6 Market area graphics—pushpin-type display.

- Railroads
- Barge lines
- Air freight
  - Passenger airlines offering freight services
  - Air cargo specialists
- Small parcel carriers
  - Ground
  - Air
  - Premium services in each
- Maritime
  - Container lines
  - Bulk carriers

The industrial engineer, in designing and/or improving a distribution system, will be concerned with most of these transport modes. Motor carriers, however, form the backbone of the entire domestic distribution system. Plants typically receive most raw materials and ship to distribution centers and customers by truck.

Deregulation

All transportation modes have been deregulated during the past 20 years. Deregulation has meant that many new carriers have emerged and are available to serve customers, regulated tariffs have been eliminated, and negotiated rates are now established by contracts between each shipper and carrier. These contractual arrangements are subject to the normal contract confidentiality customs, thus inhibiting the industrial engineer's ability to compare rates with other shippers.

Safety regulations and driver on-duty times, however, are established by law and govern all participants equally. All other things aside, the shipper's negotiating skills, detailed knowledge of the field, and sheer volume most often result in the lowest rates.

Key Cost Factors

An industrial engineer, in reviewing a transport network, has considerable freedom in developing new means of using transport capability. The engineer, however, should be aware of the key factors that influence shipping rates and transport costs. The following factors most influence transportation rates:

Volume. This is an important driver. If the transport system can be set up to accumulate larger, more frequent, full truckloads, the cost per pound or cubic foot shipped will be reduced. High volume, particularly on the same route, can be a powerful tool in negotiating lower rates.

Two-Way Movement. This is desirable to a trucker. If the engineer can couple inbound and outbound routes and volumes, lower rates can be negotiated, because the carrier will have higher equipment utilization.

Weight. Each vehicle has a maximum weight and a maximum cube that can be hauled point-to-point. In most cases, maximum weight is the driving factor, and this is generally between 40,000 and 50,000 pounds per trailer, varying because of trailer size differences and axle arrangements. For light-density products, cube determines the total cargo that can be loaded. Most trailers contain between 2500 and 4000 cubic feet.

Freight Value. This factors into the rate for insurance coverage and liability. It is possible to release the carrier from liability, which then can result in lower transport rates. It is important that the industrial engineer check for other corporate insurance that may cover cargo en route. Many companies have blanket coverage so that individual shipments do not have to be insured.

Total Inbound and Outbound Freight. It should be noted that the cost to ship product in one direction between two cities and the cost in the reverse direction are seldom the same. This is caused by the local imbalance between production and consumption. Manufacturers can use this imbalance to negotiate more favorable rates, as their freight may be more desirable to a trucker who is the victim of this imbalance. Truckers who want to reduce their costs will always favor a balanced move between two cities and thus will be open to negotiate lower rates on one leg or the other.

The Industrial Engineer's Role

The industrial engineer interested in reducing transportation cost, as distinct from the unit rate, should examine a different set of factors than the rate negotiator. A useful analogy is that of hourly wage rates and total labor cost. A manufacturer with high hourly labor rates can counteract this disadvantage by concentrating industrial engineering effort on productivity: automation, mechanization, machine utilization, and time standards. Similarly, it is possible for a company that has relatively high transport rates to experience low transport costs, because the distribution system can be designed to minimize the use of the higher rates. Again, the industrial engineer has a major opportunity to reduce high distribution and transportation costs through more effective operation design.

High transportation cost is usually a result of inefficiency in the use of the transportation system rather than of high freight rates. The main avenues for transportation cost reduction, then, are as follows:

- Accumulating freight destined for a distant location to full truckloads. This is done by the use of consolidation points, combining the freight for several customers in a locale, and sending it as a single truckload for redistribution to multiple customers from a central point in the area.
- Shipping to redistribution points one or two days a week rather than shipping each customer order immediately at a high less-than-truckload rate. Customers frequently like the better reliability of predetermined truckload sailing days rather than coping with the varying delivery times and high cost of multiple LTL shipments.
- Developing regular truck delivery routes that stop off to deliver to customers along the route. This usually requires preset delivery days.
- Redesigning the regional warehouse system to minimize the high cost of LTL freight on long hauls.
- Using combined highway/rail movement for long hauls, particularly to the West Coast from the Midwest and East.
- Increasing the loading of trucks by using larger trailers, tandem loads, high-cube trailers, and so on.
- Increasing the weight on outbound trucks by insisting they be loaded to the full visible weight or cube limit. Frequently, trucks are shipped when they reach the truckload minimum weight, about 20,000 pounds. The same truck may actually be able to take substantially more cargo, which would then ride almost free.

Industrial engineers should use the same techniques of data gathering, analysis, observation, and study to improve transportation systems that they use to improve manufacturing operations.

CONCLUSIONS AND FUTURE TRENDS

This chapter has outlined the important role that the industrial engineer can play in improving operational performance and cost in the modern distribution system. Beyond these improvements, however, is the growing potential for building a competitive advantage through adding value to the product's presentation to the market. The 1990s was a period during which customers steadily increased pressure on their suppliers to provide additional services ancillary to the simple delivery of a product order. Here are some examples of these value-added services:

- Preticketing of product and price
- Theft-deterrent tags
- Shelf packs to facilitate replenishment and customer selection
- Vendor-managed inventory and continuous replenishment programs
- Special labels for order and product identification and for directing cross-dock activities

- Direct-to-store pick, pack, and ship
- Online information on order status, advanced shipment notification, delivery status, proof of delivery, and so on
- Dock appointments at the receiving location

The industrial engineer, in planning for these services, needs to recognize that most often the customer is not willing to pay for the activity. Instead, the advantage of providing the product enhancement is to make it easier and more profitable to sell to the account. Thus, excellent, long-term business relationships can be established on the basis of mutual confidence and goodwill.

The significant trend, then, is the growing application of distribution technology and skills to increase a product's value in the marketplace. The industrial engineer must be expert in anticipating these requirements and in designing the flexible facilities that can accommodate radical change in the information systems and the physical demands of the developing distribution environment.

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BIOGRAPHY

Herbert W. Davis is founder and chairman of Herbert W. Davis and Company, Management Consultants, Fort Lee, New Jersey. He has been a materials handling and logistics consultant since 1958. During this period, he completed over 1000 assignments for 300 corporations in North America and Europe. Davis holds a B.S. degree in mechanical engineering and M.S. in industrial engineering from Stevens Institute of Technology. He serves on the Board of Executive Advisors of C. W. Post College of Management, and he is a former director of the Council of Consulting Organizations and its predecessor, ACME. Davis is a Certified Management Consultant (CMC) and a founding member of the Institute of Management Consultants. He prepared chapters for *The Distribution Management Handbook* (1994) and *Maynard's Industrial Engineering Handbook* (1992).

CHAPTER 10.5

INVENTORY MANAGEMENT AND CONTROL

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Improved inventory management and control is a key objective in every company's drive to control investment, improve cash flow, and increase profitability and return on investment. This chapter reviews the general principles of inventory management and discusses the planning, analysis, and control that are the foundation of a continuous improvement strategy for inventory management and improved profitability.

THE PURPOSE OF INVENTORY

Inventory is material or supplies that are held for future use or sales. Generally, it is finished goods waiting for a customer order. But it can also be goods or materials waiting for production or conversion into finished goods for the customer.

Not long ago, management thought inventory was a good thing; it was viewed as a valuable asset on the balance sheet. However, as business competition has intensified and costs have increased, inventory has come to be viewed somewhat differently.

The costs of inventory are tied-up capital, storage space, handling, and obsolescence—all the costs of carrying inventory. There is a significant overhead cost or burden of carrying inventory, just as there is an overhead cost associated with labor costs. Inventory in the past has been carried as a cushion or safety stock to cover up for poor planning or poor performance, to protect against uncertainty in demand or variability in the supply process.

Companies can no longer afford the luxury of excessive inventory cushions or "safety stocks" if they are to be competitive in global markets. So while some inventory may be required, managing and controlling it effectively has become a high priority. Inventory may be a necessary evil, but it carries a very high cost. And excessive inventory is cost added, a waste, a cover-up for poor planning. In fact, too much inventory may even be viewed as a liability.

Inventory is essentially a function of three things: (1) the uncertainty of demand, (2) the variability of the process, and (3) the cycle time of the process.

Three types of variability or uncertainty may require inventory: (1) demand, (2) production, and (3) supply. These are important factors in the planning, control, and management of inventory.

Customer Demand. Depending on the industry and manufacturing environment, some inventory of finished goods is usually required to fill customer orders on a timely basis. The amount or type of inventory is dictated by the need to meet or beat the competition's delivery lead time. Another factor that must be considered is the uncertainty of customer demand. So some cushion of finished goods may be planned to anticipate reasonable variations in customer demand. Remember, the better the planning and forecasting of demand for finished goods, the less inventory will be needed for uncertainty or variability of demand.

Production. The production process may have variability or uncertainty because of problems in quality, process reliability, tooling, and resource availability. An inventory of material in process provides a safety stock against uncertainties that can disrupt the production process. Proper work-in-process (WIP) inventory ensures the efficiency of a company's internal operations. Remember, the better the planning and scheduling and the shorter the cycle time, the less inventory will be needed for uncertainty or variability in production.

Supply Chain. Inventory is also required for smooth operation of the supply chain—vendor to manufacturer. Inventory in raw material may be required to protect against supply uncertainty or variability, such as vendor problems, transportation, and reliability of suppliers to allow smooth supply of raw materials and parts. The better the supply relationships with the vendors, the less raw materials inventory will be needed for uncertainty or variability in the supply chain.

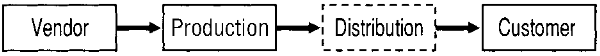


FIGURE 10.5.1 An illustration of the supply chain.

If customer demand, production requirements, and supply chain requirements (see Fig. 10.5.1) are known exactly, a company can plan requirements exactly for customer orders and will not require much additional inventory. Good inventory management means meeting customer demand with minimum inventory. Inventory investment is a function of (1) the accuracy of planning, scheduling, and execution; (2) the variability of demand, production, and supply; and (3) the cycle time of the process. Inventory investment can be used as a performance measurement tool for the quality of the planning and performance, the uncertainty or variability of the process, and the length of the cycle time. Less is better.

TYPES OF INVENTORY

Many types of inventory are found in the typical company, and they are classified and located according to their purpose or use. Three major categories apply to the inventory primarily related to a production process. See Fig. 10.5.2.

Raw Materials. Raw materials are acquired by the company in a form that needs further processing or conversion to make them part of an end product. Examples are basic raw materials to begin the production process (e.g., iron ore, crude oil, and lumber) or processed materials for general use (e.g., steel, wood, chemicals, etc.). These are materials for primary operations, and this inventory is there to protect against variability in supply.

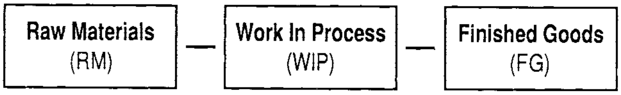


FIGURE 10.5.2 Inventory in the manufacturing production process.

Work in Process. This includes all production materials that have had some manufacturing, processing, or converting operations, but that are not yet in finished form. They are in process, and inventory protects against variability in this process. Another category that can be considered part of this inventory is often referred to as *finished parts,* meaning that they are completed parts or components that are stored to be used in the final assembly of products or may also be sold as replacement parts.

Finished Goods. This covers all completed products or finished goods produced and stored, awaiting sale or shipment to final customers. Finished-goods inventory protects against variability of customer demand.

In addition to these three major classifications, there are additional classes of inventory, which can often reside at other locations.

Service Parts. Parts, commonly called *service parts, spare parts,* or *spares,* are used to maintain the product or equipment the company sells or services. This inventory may be stored at the production location in finished parts or distributed and stocked with distributors, service locations, or locations closely involved in the repair or maintenance of the end product.

Distribution. Finished goods as well as service parts are located, stored, or in transport in warehouses throughout the distribution network. These may include those owned by the company and located away from the central manufacturing plant in branch offices, company stores, and warehouses. They include goods shipped but not yet received or invoiced by distributors, retailers, or other customers and consignment stock, or goods belonging to the manufacturer but in possession of the prospective seller on consignment.

Supplies. Items used to support or maintain operations either in the factory or in the office, but that do not become a part of the finished product, are classified by a variety of names, including *general stores* and *maintenance repair and operating* (MRO) *supplies.* They include the nonproduction items regularly stocked by the company and either consumed in operations of the plant or office or needed to maintain its buildings or equipment. These are items for plant maintenance, machine repair, plant consumables, production consumables, office supplies, and so on. The items are usually expensed.

All of these inventories must be managed and controlled with the same disciplined objective to have the material available while minimizing the investment to achieve maximum efficiency in *all* areas of the business process.

What? How Much? When? These three basic questions that drive inventory apply to all categories: raw materials, work in process, finished goods, and the like.

- *What to order.* Forecasts of finished-goods items determine replenishment orders for finished goods. The replenishment order determines what needs to be manufactured. Then this is broken down into what assemblies, subassemblies, components, and raw materials are required to produce the product. These requirements are identified by a parts list, or bill of materials, that translates assembly requirements into the raw-material requirements.
- *How much to order.* The objective in deciding how much to order is to focus on the material overhead cost—not merely the lowest purchasing cost, unit cost, or standard cost—to achieve the lowest total material cost. This requires establishing the most economical balance among the acquisition cost and the carrying cost.

  Large-order quantities enable orders to be placed infrequently and reduce acquisition and setup costs, but they increase the inventory carrying costs. Smaller quantities lower overhead and decrease the risk of obsolescence, but they require more frequent ordering and thus increase acquisition costs. For independent-demand items having regular usage, the most economical balance can usually be obtained by calculating the economic order quantity (EOQ) for the item.

Although there are a number of variations of the EOQ formula that apply to special situations, the simplest equation for determining the EOQ directly in pieces is

$$\text{EOQ} = \sqrt{\frac{2AS}{IC}}$$

where A = average annual usage, in pieces
S = setup and/or ordering costs
I = inventory carrying cost per year (as a decimal fraction)
C = unit cost of the item in dollars

This will give you the theoretical EOQ. The problem with this equation is that it assumes setup is fixed, which it is not. Setups can be worked on and reduced, and that will reduce the order quantity and the average inventory.

Thus, if we had a part with a unit cost of \$20 and an annual usage of 3000 units, a setup cost of \$50, and carrying costs of 0.5, the EOQ would be 173.

$$173 = \sqrt{\frac{2 \times 3000 \times \$50}{0.5 \times \$20}}$$

- *When to order.* The question of when to order is, When is it needed? Forecasts of when a finished-goods inventory item is needed can be used to calculate when assemblies, subassemblies, components, and raw materials are required. The bill of materials list and the lead time of each item can be used to determine when components, raw materials, or purchases are needed to meet the final production date. See Chap. 10.2 for additional information.

COST OF INVENTORY

When considering the cost of inventory, one must look beyond the obvious—the purchased cost or standard cost of material. Inventory always carries an overhead cost, usually referred to as *carrying costs;* this overhead cost typically runs up to 50 percent of the purchase cost—and this total represents the total material cost (Fig. 10.5.3). In other words, items that cost \$1, once in inventory, may really cost \$1.50. Material overhead is an additional cost added and, thus, waste. Inventory management improvement should focus on reducing the total costs, which include these material overhead costs.

Eight major overhead costs are associated with inventory.

1. *Acquisition costs.* This administrative overhead includes the cost of requisitioning, sourcing, purchasing, shipping, receiving, and the like. Acquisition costs can add 5 percent cost to the value of the inventory per year.
2. *Inspection.* This includes receiving inspection, in-process inspection, and finished-goods inspection. Inspection costs can add another 5 percent cost to the value of the inventory per year.
3. *Storage.* This is an obvious carrying cost, and it includes the cost of storage and warehouse space, security and related storage expenses, and taxes. Storage costs can vary widely, depending on the type and quantity of material and inventory stored and the kind of facility and space required. On the average, storage costs run at least another 5 percent cost to the value of the material stored per year.
4. *Handling.* All of the handling, moving, and transportation involved in controlling the inventory presents another obvious cost. It includes the wages and benefits of the personnel involved in these functions, as well as all of the material-handling systems and equipment that support their work. Handling customarily adds another 5 percent cost to the value of the inventory per year.

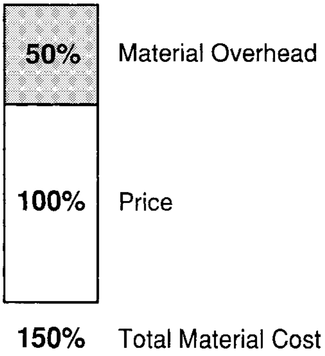


FIGURE 10.5.3 Chart representing the components of total material cost.

5. *Interest.* Inventory ties up one of a company's most versatile assets, cash. Because businesses have a limited amount of capital resources available to them from owners and creditors, capital invested in inventory carries a definite cost. It's the cost of capital. This cost is calculated as the cost of the money or the rate of return it could have earned were it invested in something else, such as government bonds or high-grade stocks. Interest costs, calculated on moderate estimates of what the capital could be expected to earn if wisely invested, add another 10 percent cost to the value of the inventory per year.
6. *Obsolescence.* Every business must face the grim fact of obsolescence to some degree. Parts in stock become obsolete because of a model change or a new product. This is particularly true in an engineered product, a high-tech product. Needs cannot be estimated with perfect accuracy, even with the most sophisticated computerized systems. Well-managed companies continuously work on surplus and obsolete inventory and dispose of it. A general rule is never to hold inventories for which there is no immediate need. Therefore, a part of the cost of inventory is an allowance to cover losses from obsolescence, which may average up to 10 percent of the value of the inventory per year.
7. *Depreciation.* In accounting terms, depreciation is the reduction in value of a capital asset based on age or usage that often may or may not reflect any real loss of value. In the case of inventory, however, depreciation refers to damage and deterioration or loss due to storage, handling, weather, age, evaporation, or shrinkage. Depreciation varies with the type of inventory, but it normally represents about 5 percent cost of the value of the inventory per year.
8. *Insurance.* Insurance on inventory is a directly variable cost because it is normally paid at a rate directly proportional to inventory value. Another factor that affects insurance cost is the kind of facilities and security systems used for storing the inventory. The insurance costs average about 5 percent of the value of material stored per year.

Thus ordering, maintaining, and controlling inventory is expensive, as you can see. Adding the total carrying costs or material overhead costs:

Material Overhead Costs	
	Percent per year
Acquisition	5
Inspection	5
Storage	5
Handling	5
Interest	10
Obsolescence	10
Depreciation	5
Insurance	5
Total overhead costs	50

These elements must be accurately calculated and analyzed to control the total material cost of all inventories.

CONCEPTS OF INVENTORY

A number of general concepts of inventory need to be explored before we proceed.

Independent Demand. Demand from the marketplace for end-product items, such as finished goods and service parts, is driven by factors that are independent of company decisions. This type of demand usually comes from relatively uniform customer orders, received continuously but also randomly throughout any time period. Forecasts of demand for these independent-demand items are typically projections based on historical demand patterns that estimate the average usage rate, usage trends, and the pattern of demand variation. The demand generally draws down the inventory until the reorder point is reached, and then a replacement order is placed and received. See Fig. 10.5.4.

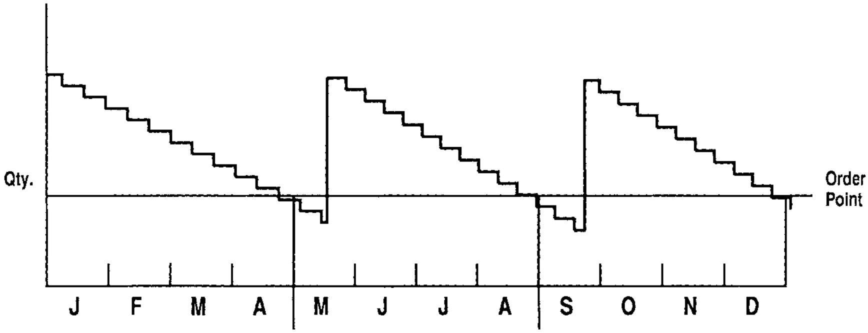


FIGURE 10.5.4 Graph showing independent-demand patterns over 1 year.

Dependent Demand. Demand in manufacturing for materials needed to make finished goods is dependent on the demand of the end-product items. These dependent-demand items are raw materials, components, and lower-level subassemblies, and they are dependent on demand for the end-product item. This type of derived demand is usually intermittent, or dependent, because demand exists only at a time when the next higher level of assembly is being made. Requirements for the lower-level material requirements are dependent on the next higher level and can be calculated based on the assembly or production of the end product. Inventory is generally planned only to meet specific production requirements. See Fig. 10.5.5.

Lead Time. A concept essential to inventory planning is lead time, or the time that it takes to replenish an inventory item. It is how long it takes to purchase or manufacture the item.

Lead time is composed of many elements. Purchased lead time includes the time it takes to source, order, receive, and enter items into stock. Manufacturing lead time adds the elements of setup time, running time, queue time, and move or transit time. The lead time is important in knowing *when* to order, so that you have the time to order and get the item.

Lead time of the product can vary based on cycle time of the process and the inventory strategy of the company to deliver the product to the market. These inventory strategies are make to stock, assemble to order, make to order, or engineer to order. See Fig. 10.5.6.

- *Make-to-stock (MTS) strategy.* The finished product is produced to stock and is in stock awaiting the customer order. This strategy produces a short customer lead time and a high

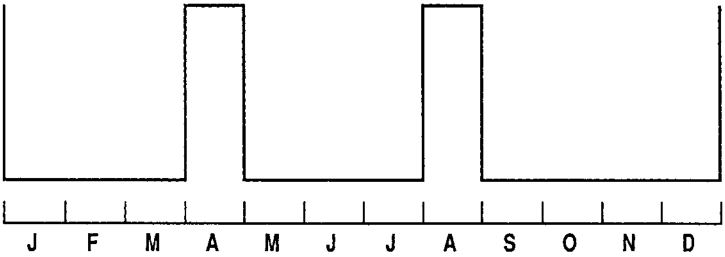


FIGURE 10.5.5 Graph showing dependent-demand patterns over 1 year.

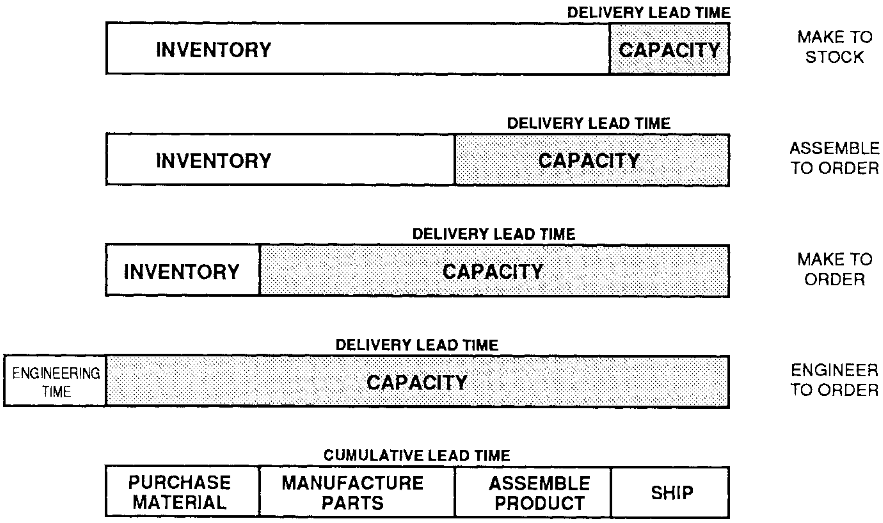

DELIVERY LEAD TIME
INVENTORY
CAPACITY
MAKE TO STOCK
DELIVERY LEAD TIME
INVENTORY
CAPACITY
ASSEMBLE TO ORDER
DELIVERY LEAD TIME
INVENTORY
CAPACITY
MAKE TO ORDER
DELIVERY LEAD TIME
ENGINEERING TIME
CAPACITY
ENGINEER TO ORDER
CUMULATIVE LEAD TIME
PURCHASE MATERIAL
MANUFACTURE PARTS
ASSEMBLE PRODUCT
SHIP

FIGURE 10.5.6 Bar chart illustrating the relationship of lead time to inventory strategy.

level of customer service. But it requires better customer demand planning with a higher level of finished inventory investment.

- *Assemble-to-order (ATO) strategy.* The important parts or subassemblies are planned in inventory but not assembled. The customer delivery lead time and customer service are good. But it requires good customer demand planning and inventory investment in components for assembly.
- *Make-to-order (MTO) strategy.* The finished product is produced after the customer order is received. It allows for specific customer orders. This strategy requires a longer customer lead time but less investment in inventory.
- *Engineer-to-order (ETO) strategy.* The product is defined, designed, planned, and produced to meet the customer's specific requirements. This strategy requires a longer lead time but virtually no prior inventory investment.

Many companies pursue more than one of these strategies and sometimes all four at once, that is, different strategies for different product lines. Proper inventory planning strategy requires that the company has an understanding of the production lead time of each product and the competitive delivery lead time in the marketplace to implement the inventory planning strategy that will maximize customer satisfaction while minimizing inventory investment.

FINISHED-GOODS INVENTORY, INDEPENDENT-DEMAND PLANNING

Finished-goods inventories that are stocked to meet customer demand are usually found in finished-goods warehouses, distribution warehouses, stocking locations, or retail environments. These inventories characteristically include a large number of items. They are the end-item stock-keeping units (SKUs) that are stocked for the customer. Their demand generally comes from many customers and is independent of other activities. Retailers can often count the number of SKUs in the hundreds and thousands when considering different variations such as sizes and colors.

Inventory management of these items relates directly to forecast demand and the level of customer service. Failing to order what is needed, in the quantity needed, at the time needed results in stockouts, poor customer service, and potential loss of sales. Conversely, ordering too much or ordering too soon will result in excessively high inventory and extra costs.

In many companies, independent-demand inventory control is heavily biased toward customer service at the cost of high inventory. Good customer service does not necessarily have to mean high inventory. Good customer service also depends on the accuracy of the demand plan (forecast) and the cycle time to replenish inventory. Another approach to excellent customer service without high inventory is to have accurate demand forecasts and short replenishment cycle times. Remember, what we want is the right amount of the right items at the right time. Customer service is really a function of the accuracy of the forecast, the replenishment cycle time, and the inventory levels. The better the forecast, the shorter the cycle time, the better the service with lower inventories.

$$\text{Customer service} = \text{forecast accuracy} + \text{cycle time} + \text{inventory levels}$$

Order Point Systems

For many years, historical data had been relied on to develop demand patterns, set order points, and determine order quantities. These basic techniques involve setting reorder points for each inventory item (this reorder point depends on the replenishment cycle time), then when stock diminishes to the reorder point, placing an order for a specified order quantity.

Setting of the reorder point is influenced by four factors: (1) the demand rate, (2) the amount of uncertainty in the demand rate, (3) the lead time required to obtain replenishment inventory, and (4) management's policies regarding acceptable inventory shortages and customer service.

$$\text{Reorder point} = \text{demand during lead time} + \text{safety stock}$$

When there is no uncertainty in either demand rate or lead time for an item, determination of the reorder point is fairly straightforward. For example, if the demand rate for an item is exactly five units per day, and the replenishment lead time is exactly 1 day, the reorder point or trigger to launch the replenishment order is five units.

Yet, constant demand rates and fixed replenishment lead times are rare in actual operations. Variations occur, not only from fluctuations in customer demand, but in replenishment lead times because of supply uncertainty. To provide protection when there is uncertainty in demand or replenishment time, the reorder point needs to be increased beyond the average demand during lead time to maintain some level of safety stock. But, remember, the objective is to have accurate forecasts with short lead times and reduced variability. This will result in lower inventories and higher-level customer service.

Order Rules

Setting of inventory levels, order points, and order quantities is central to inventory planning and management for finished goods. These are stated in order rules. This process begins with forecasting average usage or demand. The order point is set at the demand during lead time. The safety stock is determined by the variability during lead time. The order quantity is determined by the economics of production or supply.

Once these order rules are determined, the inventory management process focuses on reviewing the available stock levels against the order point. Reviewing must be done frequently because of the constant rate of depletion of stock. Some items may be checked as frequently as every issue. This is particularly true with computer systems that make this possible. Real-time data can then be reviewed as frequently as appropriate to the business—a McDonald's store uses its point-of-sale (POS) inventory system to review inventory at least daily and usually every hour. Orders to replenish inventory items from central distribution or a nearby supplier can be launched daily or even several times a day in times of heightened demand or unanticipated traffic. However, the management goal is to forecast usage accurately so that the store can run on its regular shipment until the next scheduled shipment from the central warehouse or some other source of supply.

Order rules and order points should be reviewed and recalculated on a regular basis. Computers now make it easy to analyze rates of usage and recalculate order points and order quantities frequently to keep pace with changes in customer demand, replenishment cycle time, and other changes in the consumer environment.

There are several types of order rules and many variations of each, because any given situation or class of inventory may require different types of order rules involving differences in inventory levels and total inventory costs. The order rules most commonly applied in the distribution and retail environment are based on fixed order quantities and fixed order cycles or intervals.

Fixed Order Quantity. In some systems, the order point establishes when to order the inventory. When the stock on hand falls to the reorder point, the inventory planner places a reorder. How much to order is prescribed by a predetermined economic order quantity (EOQ). The EOQ is calculated as the quantity that will result in the lowest total costs of acquiring, producing, or carrying the item. Thus, the order quantity is fixed and the time interval between orders may vary, depending on the rate of usage.

A good example of fixed order quantity inventory management can be seen in the maintenance of service parts at an auto dealer. When stock of a particular part, such as a gasket, reaches the reorder point for that item, it automatically orders an EOQ from the distribution center. The inventory control system may be as simple as a two-bin system. When one bin is depleted, the order is issued for replenishment inventory.

The advantage of the fixed order quantity for managing inventory is that it is flexible. Orders can be issued any time. When the order point is reached, an order is generated. Thus, the order cycle may vary, but the order quantity does not. The nature of some businesses may also require that they develop separate order points and order quantities on items for different times of the year because of different (seasonal) usage rates.

Fixed Order Cycle. In some distribution systems, ordering takes place at a fixed interval or cycle. When this rule is used, items are ordered at regular fixed cycles, such as every week. The specified interval indicates when to order. How much to order is determined by subtracting the stock on hand to determine an order amount to meet an established or target inventory level. In this case, the order quantity may vary, but the order review cycle is fixed.

A good example of fixed order cycle inventory management can be seen in the stocking of bread to retail outlets. Each retail site is visited by the bread distributor's representative on a predetermined schedule. The representative checks the loaves on the shelf, removes any outdated stock, and adds to what remains the quantity required to bring it to the desired inventory level. The replenishment quantity may vary from order to order (depending on the usage), but the interval at which the representative revisits, checks, and brings up the stock is fixed.

Fixed order cycle inventory management is most useful in situations where there are a large number of items that are ordered and delivered at one time, and there are no significant economies from ordering individual items in larger quantities.

Order point continues to be used in many companies for managing independent-demand finished-goods items, service parts, supplies, and stable-usage items. While it may be executed manually, many companies now track finished-goods sales and inventories on computers, aided in the retail and warehouse environment by POS terminals, scanners, or bar-code readers for real-time data capture. The computers track on-hand inventory at all sales locations and provide automatic reorder messages to trigger replenishment orders and the proper distribution of inventory throughout the entire distribution system or supply chain.

DEPENDENT-DEMAND INVENTORY PLANNING

For many years, the same order point method was utilized for managing both independent-demand finished-goods and dependent-demand raw-materials inventories. There were a number of problems, however, with using order point for these dependent-demand items. First, the approach is not oriented to future demand. It's based on historical usage. Second, and most important, it does not recognize the dependent-demand relationship. The lower-level components and raw materials are not needed in inventory until they are required for the next higher level. Their demand is dependent on the higher-level parent. With the advent of computers, we are now able to plan more effectively and calculate dependent-demand inventories based on these dependent relationships.

The Closed-Loop Inventory Planning System

First came computer-based material requirements planning (MRP) in the 1960s and 1970s. This shifted emphasis from order points and launching orders when an item appeared to be running out to scheduling and priority planning based on due dates for finished products and due dates for components and raw materials.

Next came manufacturing resource planning (MRP II) in the 1970s and 1980s. This expanded the scope of planning and control to encompass all functions of the company, including sales, manufacturing, engineering, purchasing, and production. This enabled management to integrate long-term, medium-term, and short-term planning into a total-company closed-loop inventory planning system.

Then came enterprise resource planning (ERP) in the 1990s, which expanded the scope of planning and control to the entire enterprise. The current computer systems have migrated to the ERP model.

The closed-loop system translates top management planning into a business plan, sales plan, and production plan for finished goods into rates of production that must be established and produced by operations management to meet customer demand. This is the *what, how much,* and *when* of the rates of finished products or finished goods by month that are needed for the company. See Fig. 10.5.7.

The next step is the heart of the computer-based inventory planning system. Operations management planning develops the master schedule of what, how much and when, which is the weekly detail statement of the mix of products to be produced, and then this schedule is

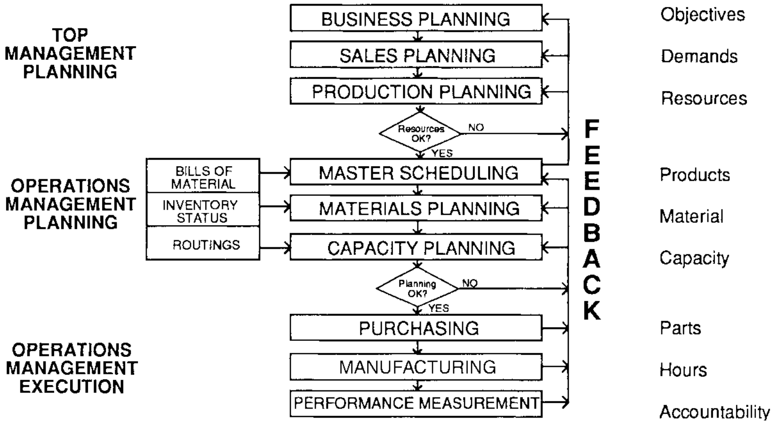

TOP MANAGEMENT PLANNING
BUSINESS PLANNING
SALES PLANNING
PRODUCTION PLANNING
Resources OK?
NO
YES
OPERATIONS MANAGEMENT PLANNING
BILLS OF MATERIAL
INVENTORY STATUS
ROUTINGS
MASTER SCHEDULING
MATERIALS PLANNING
CAPACITY PLANNING
Planning OK?
NO
YES
OPERATIONS MANAGEMENT EXECUTION
PURCHASING
MANUFACTURING
PERFORMANCE MEASUREMENT
FEEDBACK
Objectives
Demands
Resources
Products
Material
Capacity
Parts
Hours
Accountability

FIGURE 10.5.7 Chart presenting the closed-loop inventory planning system.

exploded into the detail materials plan and capacity plan. Material planning is a time-phased priority planning system to schedule material to meet requirements. Capacity planning provides detail capacity requirements of labor and equipment to produce the product.

In the computer-based inventory planning system, these activities are supported by information in a database, which includes bills of material, inventory status, and routings. The bill of materials specifies the parts or materials needed to produce the final product. Routings specify the process or the operations in production. And the inventory status includes the on-hand quantity and location of the items in raw material, work in process, and finished goods that are available to produce the product.

Operations management execution is the final step, which develops daily schedules of inventory and production for purchasing and manufacturing. Purchasing then purchases the materials and parts required to support the inventory plan, and manufacturing moves the raw materials and subassemblies through the production process to meet daily schedules and produce the final product to meet the inventory plan. Performance measurement provides the monitoring device to review and communicate that all functions are performing to plans and to meet customer demand.

A computer-based closed-loop inventory planning system can provide much better planning and control of dependent-demand inventories. The computer takes over the multistep task of calculating requirements for all the parts through the bills of material, maintaining inventory record status, and projecting material and capacity requirements to produce the product.

ACHIEVING ACCURATE INVENTORY

Accurate inventory records are very important for a company's inventory management. They are important for many reasons:

- They verify the physical inventory as an asset in determining the value of a company.
- Customer orders for products can be accurately quoted and shipped from inventory.
- Realistic production schedules can be developed and met because people can count on having the necessary parts and materials available in inventory when needed.
- Production delays caused by unexpected shortages of critical materials can be eliminated and the need for costly, last-minute rush orders can be reduced.
- Inventory levels can be reduced because "safety" stocks held to compensate for unexpected shortages or incorrect balance information are not needed.
- Improved production efficiency, product quality, productivity, and customer service can result.

Effective inventory control depends upon accurate and timely inventory information. A key measurement of inventory control is inventory record accuracy.

Measuring inventory accuracy is a two-step process. First, the inventory items are physically counted. Next, the count is compared with the balances shown on the inventory records. When the counts match the balances shown on the inventory records exactly or within predetermined tolerance ranges, the inventory is accurate. Inventory accuracy of at least 95 percent is generally considered mandatory for effective inventory planning and control.

Inventory Transaction Processing System (TPS)

An inventory transaction processing system is required to track the movement, location, quantity, and status of materials and parts as they physically move through the production process. The transaction processing system relies on people, processes, procedures, and computers to accurately account for the physical transfer of materials within the production process.

Inventory transaction systems should be simple and transparent and should reflect reality. A blueprint or layout of the facility is a handy starting point for identifying material flows and inventory control points. Inventory control points are anyplace where materials are transferred, such as the receiving dock, controlled stockroom areas, and the shipping dock. As material passes through an inventory control point, it should be documented and recorded by a transaction to maintain accurate inventory information.

Transaction information should include identification of the part number being moved, quantity, its location, and the material's status. For example, when an item is received into the warehouse, a transaction should be recorded specifying the part number of the item and how many are being received into that stock location.

Controlled stockrooms can be helpful in improving inventory accuracy defined by physical barriers such as fences or by psychological barriers such as lines painted on the floor, signs on the walls, or other markings. Employees in each controlled stockroom are responsible for recording the appropriate transaction information any time materials move in or out of the area. The inventory accuracy of each controlled stockroom area should be measured, and performance results posted in each area for accountability.

Transaction recording can be facilitated through the use of bar coding, scanners, and optical character readers. This enhances both the accuracy and timeliness of the data capture. Paper forms may still be necessary under some circumstances, however. The following are guidelines for designing paper transaction forms:

- Develop simple single-use forms. To minimize errors, a different form or paper color should be provided for each transaction type.
- Make directions and field titles simple and easy to understand.
- Minimize the amount of writing necessary to complete the forms. Preprint as much information as possible.
- Organize the fields on the forms so that they can be completed in order as stockroom personnel receive or issue materials.
- Make forms computer-scannable or clearly arrange the fields to match the computer system's input screens to facilitate accurate data entry.

To ensure that the inventory transaction system is up to date, transactions should be processed on a timely basis. Timely TPS is important for accurate inventory records and for audit reconciliation. Most inventory transaction systems generate a transaction audit trail for reconciling the inventory and identifying and correcting errors. The paper transaction documents completed by employees as materials move through the production process serve as a valuable, physical audit trail. These documents can be maintained in a file for reference whenever discrepancies are detected in the computerized records.

Transaction history reports can be generated detailing all transaction activity affecting on-hand balances. Reports by part number and location are also useful for identifying and correcting errors. Remember, the objective is to maintain accurate inventories, not to generate transactions and documents. Value added—not cost added. Less is more.

A number of methods can be used to verify the inventory. The two most frequently used procedures are the annual physical inventory and cycle counting.

Annual Physical Inventory (API)

Traditionally, manufacturers closed their plants for a number of days to physically count and verify their inventories. Discrepancies between the dollar value of materials counted on hand and of inventory on the books were reconciled. The books were adjusted as necessary. The purpose of the annual inventory was to ensure that the company's books were accurate for accounting and tax purposes. The primary emphasis of this approach was on total dollar value of the inventory.

Today's competitive manufacturing environment requires a much different and higher degree of inventory accuracy. Managers require correct inventory information by item at all times to ensure the quality of their planning, scheduling, and control decisions. Inventory information that is reliable only once a year and only by total dollar value is of little use for modern production and distribution planning.

The accuracy of inventory balance information determined by an API is often questionable, even on the day that the inventory is completed. Because the annual inventory occurs only once a year, it is taken by numerous employees who are generally untrained in inventory taking. Counting and identification errors are likely to result, and the API has always been suspect. Despite the massive effort involved and loss of production time while the plant is shut down, the major problem with the API is that no ongoing problem-solving and accuracy improvements are likely to result. The API does not promote an ongoing process of continuous improvement and keeping the inventory accurate throughout the entire year.

Cycle Counting

In place of the API, today's companies use a process called *cycle counting,* a proven method that helps maintain inventory accuracy over time. Cycle counting relies on continuous counts, or audits of the inventory, on a regular basis throughout the year. These counts are compared with the balances shown on the computerized inventory records. Any discrepancies are analyzed immediately to determine what caused the errors, and steps are taken to fix the error and prevent it from occurring again.

$$\text{Inventory record accuracy} = \frac{\text{number of records correct} \times 100}{\text{number of inventory items}}$$

Examples of accuracy tolerances for inventory items classified using the ABC method are shown in Table 10.5.1. Inventory records showing on-hand balances that match the physical count or fall within the tolerance range are considered accurate. Notice that 0 percent tolerance is allowed for high-dollar-value items (class A). The wider tolerance range for class C items, 5 percent, reflects both their lower dollar value and the fact that weigh counting is routinely used instead of physical counting to determine both actual and transaction quantities for these items.

Inventory accuracy can also be measured by comparing the dollar value of inventory on hand, as shown by the inventory records, with the dollar value of the physical inventory. However, this measurement is not particularly useful for efficient manufacturing and improving inventory accuracy. As shown in the last column of Table 10.5.1, inventory accuracy measured in dollars produces a higher level of rate accuracy than count accuracy. For inventory control purposes, the count accuracy of on-hand balance by item by location is the important measurement, much more so than the dollar accuracy of the financial statements.

TABLE 10.5.1 Examples of Accuracy Tolerances for Inventory Items Classified by the ABC Method

Control		Count analysis			Dollar analysis		
Value class	Tolerance	Parts counted	Within # limit	Count accuracy	On hand (in dollars)	Variance (in dollars)	Accuracy (in dollars)
A	0%	50	49	98%	7500	75	99%
B	2%	75	72	96%	2000	(100)	95%
C	5%	100	93	93%	500	(50)	90%
Total		225	214	95%	10,000	(75)	99%

Remember, take care of the piece count accuracy, and the dollar accuracy will take care of itself.

Benefits of cycle counting in contrast to an API include

- Efficient use of trained personnel
- Regular error detection and correction
- Minimal loss of production time
- Improved inventory accuracy
- Reduced inventory levels
- Better productivity
- Improved customer service

Control Group Method

Before implementing a full-scale cycle counting program for all inventory, it is a good idea to select a small sample control group of items for daily counting and reconciliation to prove the process and identify any problems. For example, a group of about 50 items, ranging in volume, price, and size from large to small, may be counted and reconciled. Differences between the counts and the balances shown on the computerized inventory records should be identified and corrected on a daily basis for this control group.

ABC method. This method maximizes dollar inventory accuracy while minimizing the effort and cost required for counting. Items are categorized as class A, B, or C, based on their dollar value. Class A items are counted most frequently, perhaps monthly, because they are usually about 10 percent of all inventory items that account for 60 to 75 percent of the total dollar value of inventory. Class B items are counted somewhat less often, perhaps quarterly. Class B items account for 20 percent of inventory items but comprise 20 percent of the inventory's total dollar value. Class C items are counted least often, perhaps only once or twice per year. Class C consists of the low-dollar-value items that make up the remaining 70 percent of the total inventory items.

Reorder method. The reorder selection method is designed to minimize the number of items that must be counted with each count. Using this technique, inventory items are counted whenever a reorder is issued, and the inventory is usually at the lowest level requiring the counting of the fewest number of items. Another advantage of this method is that when a quantity discrepancy is identified, there may still be time to prevent a stockout.

Free-count method. Using the free-count method, stockroom personnel count inventory items whenever they are servicing the inventory at a location, such as when a replenishment lot is received or when pulling the last item from a location—thus, a "free" count.

Zone-count method. This is cycle counting by location or zone. On a rotating basis, each zone's contents are counted. This method is used because zones keep the counting concentrated in one area. Also, inventory accuracy accountability is usually assigned by area. This is probably the best method.

Other methods. In addition to dollar value, some companies may use classification criteria such as how critical an item is to the finished product, length of procurement lead time, or amount of storage space required.

Items should also be counted whenever an error condition has been identified or a problem exists. For example, if the computerized inventory records show a negative balance on hand for a particular item or a quantity on hand without a valid stockroom location, the actual inventory status should be investigated and the records corrected.

Process of Continuous Improvement

The objective is to fix the problems that are causing the discrepancies—which involves far more than just adjusting the numbers to bring them into balance. Once the problems are resolved, the records will begin to stay accurate on an ongoing basis.

Once inventory accuracy of at least 95 percent is consistently maintained for the small sample control group, then a full-scale cycle counting program can be launched that encompasses all the inventory. Various criteria can be used to select and schedule the inventory items that will be counted. These criteria include the ABC selection method, the reorder selection method, free counting, zone counting, and others.

Measuring Performance

Inventory accuracy is a measurement of performance indicating the accuracy of inventory balances on hand. Actual inventory should be compared with the balances shown on the inventory records at least once per year by physically counting the items. The measurement is expressed as the percentage of correct record balances. Correct on-hand balances are those that match, within preestablished tolerance ranges, the actual number of items on hand.

INVENTORY MANAGEMENT AND ANALYSIS

Inventory management and analysis are an important part of the management function. Timely inventory analysis enables managers to identify and control inventory investment problems. By monitoring and controlling inventory investment levels, turnover rates, lead times, and days of stock, many companies can significantly reduce their inventory investment and their total inventory investment costs.

Inventory Flow Model

Modeling has been used for analysis in many areas of management, and it is also an important tool for inventory management and analysis. Inventory models can be used to plan inventory levels and to highlight problem areas, such as inventory buildups or inventory imbalances. The purpose of the inventory flow model is to model the present inventory against the inventory flow rates to detect problems with the inventory. The information needed to construct the model is material, labor and overhead costs as a percentage of cost of sales, the annual volume, and the present inventory levels. This information is used to model each category of the present inventory—raw materials, work in process, and finished goods—and to establish inventory targets for each category and for the total inventory. See Fig. 10.5.8.

- *Materials cost.* As a percentage of cost of sales, figure generally 50 to 60 percent.
- *Labor cost.* As a percentage of cost of sales, figure generally 5 to 10 percent.
- *Overhead cost.* As a percentage of cost of sales, figure generally 30 to 45 percent.
- *Cost of sales dollar volume.* The annual total dollar volume in cost of sales (COS) divided by 12 gives the monthly total volume in COS rate, and that divided by 20 gives the daily COS rate.
- *Flow percentage.* The flow percentage for raw materials (RM) is the percent that RM is of the total cost of goods. In the example, 50 percent. The flow percent for finished goods is 100 percent. The flow percent for work-in-process is the RM flow rate plus one-half the difference between the RM rate and the finished goods (FG) rate, or 50 percent plus ½ of 100 minus 50 percent = 75 percent.
- *Flow rates per day.* Divide the flow percentage for each category into the total flow rate per day to determine the dollar flow rate per day for each category.

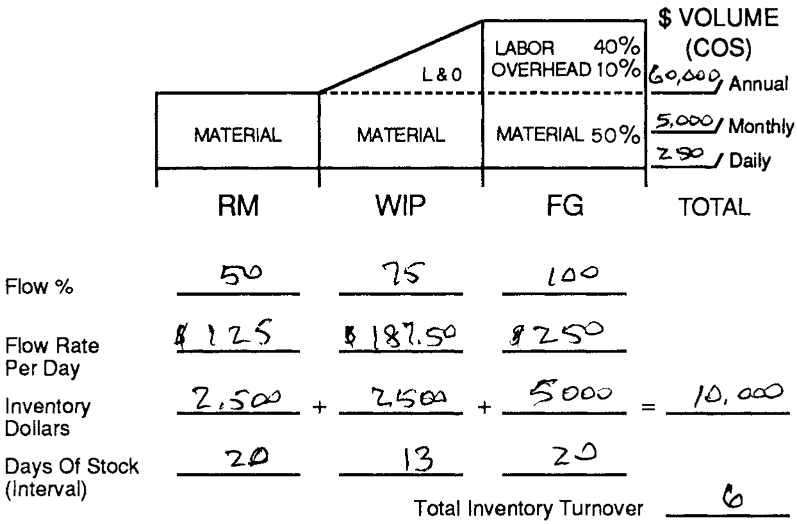

$ VOLUME (COS)
LABOR 40%
OVERHEAD 10%
L & O
60,000 / Annual
5,000 / Monthly
250 / Daily
MATERIAL
MATERIAL
MATERIAL 50%
RM
WIP
FG
TOTAL
Flow %
50
75
100
Flow Rate Per Day
$125
$187.50
$250
Inventory Dollars
2,500 + 2,500 + 5000 = 10,000
Days Of Stock (Interval)
20
13
20
Total Inventory Turnover
6

FIGURE 10.5.8 A basic inventory flow model.

- *Inventory dollars.* The actual inventory dollars on hand by category of inventory and the inventory in total.
- *Raw materials.* The RM inventory divided by the RM flow rate per day equals the number of days of stock in raw materials, or $2500 divided by $125 per day equals 20 days of inventory.
- *Work in process.* The number of days of inventory are determined in the same way as raw materials. In this case, $2500 divided by $187.50 equals 13 days.
- *Finished goods.* The finished goods inventory is divided by the finished goods flow rate per day, which is full cost (material + labor + overhead), to determine the number of days stock in finished goods, or $5000 ÷ $250 = 20 days.
- *Inventory turnover.* Inventory turnover is the ratio of annualized COS to inventory investment.

$$\text{Turnover} = \frac{\text{COS}}{\text{total inventory}}$$

You can also calculate turnover of each category of inventory by dividing by the annualized COS of the inventory for that category.

$$\text{Turnover} = \frac{\text{inventory COS}}{\text{inventory category}}$$

This inventory flow model can be used to answer the following questions: What is the inventory by category and in total? What should the inventory be by category in total? What should the days of stock and cycle time be? What actions can be taken to reduce the cycle time, days of stock, and inventory for each category of inventory and the total inventory?

Inventory Model

Inventory models can also be used by managers to construct inventory plans by category to monitor each category of inventory and the total inventory in the company. These inventory models make it easy to track planned to actual performance on a monthly basis to see if levels are being controlled and managed according to plan. See Fig. 10.5.9.

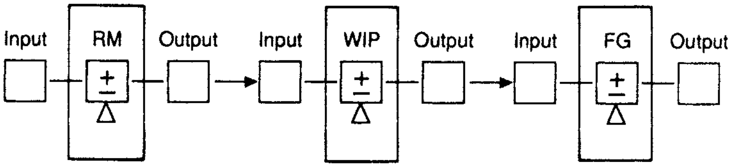


FIGURE 10.5.9 A flow model for the input-output process.

STRATIFICATION ANALYSIS—ABC

Vilfredo Pareto was an Italian economist who said that a small percentage of a group's items contributes the bulk of its costs, value, impact, and the like. This rule (Pareto's law) has many applications. For example, a small percentage of customers are often responsible for the largest percentage of sales volume. Similarly, a small percentage of out-of-stock items are generally the cause of the largest percentage of back orders.

In the typical manufacturing and distribution company, it is generally true that 20 percent of inventory items may account for 80 percent of inventory value while 80 percent of inventory items may account for only 20 percent of the value. Stratification analysis applies this rule in a time-honored tool of inventory management.

ABC Analysis

Inventory items are categorized by their annual dollar volume. An ABC analysis lists inventory items in decreasing dollar-volume order and labels the high-dollar-volume items as "A," medium-dollar-volume items as "B," and low-dollar-volume items as "C." To generate an ABC analysis report:

1. Calculate annual dollar volume for each inventory item by multiplying the item's unit cost by its annual usage volume.
2. Generate a report in decreasing dollar-volume sequence showing item numbers, annual usage, unit costs, annual dollar volumes, and item counts.
3. Compute cumulative totals and percentages for item counts and annual dollar volumes on an item-by-item basis. The purpose of this step is to separate the three inventory classes. It is not necessary to perform these calculations for every item on the list—see step 4.
4. Delineate the A, B, and C categories based on cumulative item count and volume percentages. For example, a manufacturer may decide to place 10 percent of total inventory items in class A, 30 percent in class B, and 60 percent in class C. Because the items have already been sorted into decreasing dollar-volume order, the small percentage of items in class A will generally account for a large percentage of annual dollar volume, often as much as 80 percent or more.

Based on an ABC analysis of inventory, management can implement appropriate planning and control procedures for each class of inventory.

Class A items receive the most attention, because they account for the largest dollar volume yet are relatively few in number. By increasing control over class A items, fewer can be kept in stock. Managers can best leverage their time spent controlling inventory by concentrating on these high-dollar-volume items. In this way, management can apply greater control over ordering and controlling costs to reduce the total material cost of the inventory.

Total Materials Cost and Turnover. The information generated by an ABC analysis of inventory is a useful starting point for analyzing the effects on total material cost of different inventory investment and inventory turnover rates on different classes of inventory. Table 10.5.2 shows a sample company's class A, B, C inventory classifications. It shows the turnover (TO) and order index using the normal approach, and it shows the turnover and order index using the total material cost—turnover (TMC-TO) approach. The order index is determined by multiplying the percentage of total inventory items for a category by the turnover rate for the category. The order index is an indicator of the ordering and controlling costs for a category of products. The lower the index, the lower the ordering and controlling costs. Notice the contrasting effects on the order index. When the turnover for all three inventory items is six times per year, the order index is 600. Using the ABC concept of inventory control, the order index is reduced to 420, a reduction of 30 percent. The turnover of A items is increased to 12 times a year. This shows under the TMC-TO column. The overall TMC turnover is increased to 8.5 times per year, an increase of 40 percent.

TABLE 10.5.2 Chart Showing Total Material Cost As Applied to Inventory Turnover by Inventory Class

% dollars	% item	Class	TO	Order index	TMC-TO	Order index
70%	5%	A	6	30	12	60
25%	25%	B	6	150	6	150
5%	70%	C	6	420	3	210
100%	100%		6	600	8.5	420

Table 10.5.3 shows how the savings in Table 10.5.2 were accomplished by introducing the dollar values for the three inventory categories. By focusing attention on the A items, it was possible to increase their turnover from 6 to 12 times per year. Because less attention was given to the C items, their turnover dropped to only 3 times per year. But since they constitute only a small dollar value, the total TMC-TO increased from an average of 6 to 8.5 times per year. The inventory levels are reduced by 30 percent.

TABLE 10.5.3 Chart Showing Savings Made in Inventory Levels by Using the ABC Categories of Inventory Controls

% dollars	Dollars	Class	TO	Inventory levels	TMC-TO	Inventory levels
70%	$10,500,000	A	6	$1,750,000	12	$875,000
25%	3,750,000	B	6	625,000	6	625,000
5%	750,000	C	6	125,000	3	250,000
100%	$15,000,000		6	$2,500,000	8.5	$1,750,000

This is balancing the inventory carrying costs with the ordering and acquisition costs by class of inventory to achieve lowest total material costs (TMC = acquisition costs + carrying costs).

The total result of applying the TMC-TO concept is to reduce the inventory and inventory carrying costs by 30 percent and also reduce the acquisition costs or ordering and controlling costs by 40 percent—working smarter, not harder.

SURPLUS AND OBSOLETE (CLASS D) INVENTORY

For inventory management and control purposes, there is another class of inventory. This is the surplus and obsolete inventory, sometimes called class D.

Surplus Inventory

This is usable inventory, but extra or surplus stock that is on hand above the normal usage rate—usually for the next year. Because there is no forecast requirement for this inventory within the next year, keeping the surplus or slow-moving items on hand merely increases total inventory carrying costs. Surplus items held for too long can eventually become obsolete.

Obsolete Inventory

This consists of items that are no longer in demand. This may be because the items are perishable, have a shelf life and have expired, or because they are no longer stylish or have become technologically obsolete. They may no longer be used in products because of an engineering change.

Obsolescence is an acute problem for consumer products. By law, many products carry expiration dates. Such items include film, canned goods, drugs, and food and dairy products. Once these goods pass their expiration dates, they are unsalable, obsolete, and must be written off and destroyed.

Stylish items and high-tech goods can become obsolete quickly because of changing styles and their short product life cycles. Examples of these items are clothing, cosmetics, electronics, and computers. Current sales of these types of products are not always accurate predictors of continued future demand.

Companies often write off as much as 10 percent or more of the value of their total inventories each year due to obsolescence. This comes right off the bottom-line profits. While some obsolescence may be unavoidable, many companies find they can reduce their write-offs to 5 percent or even less through better inventory control.

Many companies have accounting reserves for surplus and obsolete inventories in anticipation of writing off 25 percent per year for 4 years to provide for this total loss. The objective should be to reduce surplus and obsolete inventory by determining its causes and fixing the cause, whenever possible. Internal problems, such as inaccurate bills of material or engineering changes, and overproduction can be identified and corrected. Even unexpected changes in external demand should be identified and managed by prompt recognition and action. At a minimum, further acquisitions of materials for which there is no longer a forecast need should be stopped immediately.

Early warning systems that detect potential slow-moving and surplus items enable managers to take preventive action before items become surplus and obsolete. Management should carefully evaluate disposal alternatives for any items that do become surplus or obsolete to determine the most profitable recovery of the asset value.

Opportunity to Fix Causes

An earnest effort should be made to identify obsolete and surplus inventory so that its causes can be analyzed and remedied. For independent-demand finished-goods items, differences between forecast and actual demand can cause surplus and obsolete inventory in finished goods. For dependent-demand items, differences between planned and actual usage can result in surplus or obsolescence in work in process or raw materials.

Analyzing significant variances of both types may reveal that some plans did not materialize, products changed, or the process was not managed properly, resulting in surpluses building up.

One of the major causes of surpluses and obsolescence is poor timing of engineering changes. Companies should time style, design, or package changes to make the best possible use of existing inventory. Whenever changes are planned, all of the affected functions should be consulted to determine optimal timing for the change. Change information and dates should be based on using up existing inventory and should be communicated accurately to all the relevant functions. Otherwise, surplus and obsolete inventory will result, which will eventually have to be written off.

Another contributor to surplus and obsolete inventory is overbuying and overproduction. The benefits of placing or making large orders must be balanced against the risk of obsolescence. In this case, increasing order frequency and decreasing order quantity may lead to a decrease in total materials cost with less risk of surplus or obsolescence.

Solutions

Unfortunately, class D inventory is often identified after the fact. Surplus inventory becomes obsolete as expiration dates pass and demand drops. Companies can be in for an unpleasant surprise when they take an API and discover large quantities of unsalable and unsalvageable goods. The sizable write-offs that can result may be prevented by detecting surpluses earlier and timing changes to occur after existing inventories are depleted.

Once detected, surplus and obsolete items should be disposed of as profitably as possible. If an item can be used as is, 90 percent or more of its former dollar value may be realized. For example, a part that is no longer needed because of an engineering change may still be salable to dealers as a pair or replacement part. If an item is unusable as is, reworking it for a different use or returning it to the vendor may net the company 75 percent of the item's former value. The next option is disposing of or selling the item at 25 to 50 percent of its former value. Offering a nearly obsolete item at a deep discount may make it attractive to customers or other manufacturers. The last resort is scrapping the item. However, this is the least desirable alternative. Only 10 percent or less of the item's initial value may be recovered this way.

Early detection of surplus and obsolescence makes it possible to realize more of an item's original value upon disposal. If the problem is detected soon enough, the item can still be used, reworked, or returned. Timely action has been known to reduce write-offs from 10 down to 2 percent of an inventory's total value. See Table 10.5.4.

TABLE 10.5.4 Chart Showing Options and Recovery Values for Disposing of Surplus and Obsolete Inventory Value

Disposition	Recovery	Loss
Use as is	100%	0
Rework/return to vendor	75%	25%
Sell/disposal	25–50%	50–75%
Scrap	10%	90%

How can managers identify potential inventory problems while there is still time to react? One solution is to analyze the inventory against the projected or forecast usage to identify the items with no usage (potentially obsolete) and the items with inventory greater than 1 year's usage (potentially surplus). This analysis should be done at least once a year.

Remember, the objective is to eliminate or minimize the actions that cause surplus and obsolete inventory in the first place, and then dispose of the existing surplus and obsolete inventory for maximum value and minimum loss.

PERFORMANCE MEASUREMENT

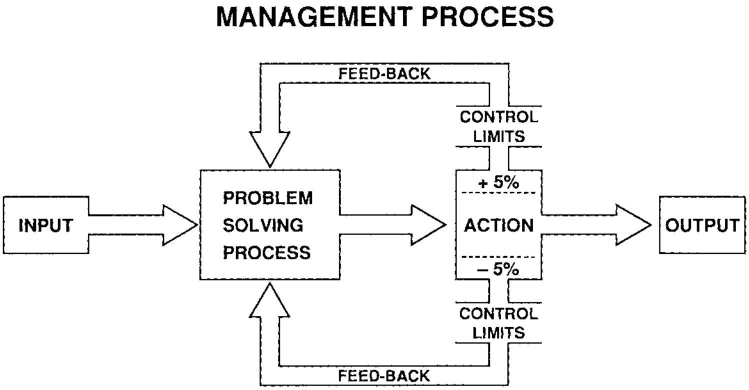
Inventory management is a closed-loop process that consists of setting objectives and tolerance limits, developing action plans, allocating resources, assigning responsibilities, implementing plans, and finally, measuring performance in order to provide feedback for corrective action.

Today's computer-based inventory planning systems present companies with unprecedented capabilities for planning inventory and reporting conformance to plan on important inventory performance measurements. See Fig. 10.5.10. Improving inventory management is a five-step process:

1. Establish measurable objectives.
2. Measure present performance.
3. Identify problem performance areas.

4. Develop an action plan with resources and responsibilities for solving the problem performance areas.
5. Measure performance on a regular basis and repeat steps 3 through 5.

Performance objectives should include a quantifiable performance target and the date when the target should be achieved. For example, a company may specify that it plans to increase inventory accuracy to 75 percent by June 1 and to 95 percent by December 1 or reduce inventory levels by 25 percent by the end of the year.



PROBLEM SOLVING PROCESS

1.) Define Problem
2.) Identify Facts
3.) Determine Alternatives
4.) Evaluate Alternatives
5.) Select Best Alternative
6.) Simulate or Pilot Alternative
7.) Implement Plan
8.) Feed-Back & Follow-Up

FIGURE 10.5.10 Performance management process.

There are a number of important performance measurement techniques that can be used to measure inventory performance.

Inventory Accuracy

This is a performance measurement indicating the accuracy of inventory balances on hand. The balances shown on the inventory records are compared with actual quantities on hand, determined at least once per year by physically counting the items. The measurement is expressed as the percentage of correct record balances. Correct on-hand balances are those that match, within preestablished tolerance ranges, the actual number of items on hand.

$$\text{Inventory accuracy} = \frac{\text{number of records correct} \times 100}{\text{number of inventory items counted}}$$

Most companies target for at least 95 percent inventory accuracy.

Inventory Investment

This compares actual inventory with planned inventory investment. The dollar value of each category of inventory and total inventory is tracked on a monthly basis, usually against a model, and a variance is calculated from the planned inventory investment.

$$\text{Performance to plan} = \frac{\text{actual inventory}}{\text{planned inventory}}$$

Inventory Turnover

This is the ratio of annualized cost of goods sold to the cost of average inventory on hand for a given time period. Inventory turnover can also be calculated for each category of inventory or for the total inventory.

$$\text{Turnover} = \frac{\text{cost of goods sold}}{\text{average inventory on hand}}$$

Although the appropriate number of inventory turns varies by company and industry, a company's goal should be to continually increase the number of inventory turns while maintaining high-quality customer service. By increasing inventory turns, a company decreases its inventory investment and its total inventory investment costs. Inventory turnover can also be benchmarked against others in the industry to determine the performance in the industry.

Cycle Time

This is another measure of the quality of inventory management. Cycle time can be measured in weeks or even days of stock. One way to measure cycle time is to simply measure the time a product is in the process. Another method of determining the cycle time is derived by dividing the number of days in the year by the number of inventory turns. For example, there are 360 days in a year so the company with 4 inventory turns has a cycle time of 90 days—3 months' worth of supply, or 90 days of stock. Cycle times for individual categories of inventory can also be calculated and reviewed.

Most companies strive to reduce cycle times, which is accomplished by improving the inventory flow and eliminating the wasted time in the process. Remember, inventory is a function of cycle time. If you want to reduce inventory investment, work on cycle times.

Inventory Modeling

Inventory models are powerful tools for improving inventory management. Graphic representations of current inventory status are also useful for zeroing in on problem areas, such as raw-material, work-in-process, or finished-goods buildups, and identifying problems that cause unfavorable variances from performance objectives. Managers can use these models to determine and reevaluate optimal inventory levels and inventory policies to meet changing demands in the marketplace.

An inventory flow model shows the company's dollar investment in each type of inventory as a function of cycle time. The purpose of the flow model is to show the inventory investment by category of inventory both in total inventory dollars and in days of stock. The monthly inventory reports should show the actual inventory dollars by category of inventory and in total inventory against the plan. Based on this information, companies can make important inventory management decisions.

Another type of graphic inventory model is a cycle time bar chart showing the sequence and duration of the production process, materials movement, and queue time in the production of the product. This type of chart is useful for identifying steps that should be shortened or eliminated because they do not add value to the product. The goal of this process is to reduce the cycle time of the product and thus reduce the inventory.

A bar, or line, chart is another type of graphic inventory model that compares actual with planned performance. Measurements such as inventory investment, inventory turnover, and inventory accuracy can be charted and analyzed on a month-by-month basis to evaluate performance against plan and identify trends.

Performance measurements serve both diagnostic and motivational purposes. Once a company identifies areas of inventory that require improvement, the next step is to develop action plans for meeting performance improvement objectives. To provide necessary feedback to the employees and managers responsible for carrying out the plans, charts showing actual versus targeted performance should be posted on boards and in stockrooms. Managers should also receive detailed monthly reports and an analysis of problem areas for feedback to improve performance.

Improvements in inventory management can provide significant contributions to a company's bottom line. As long as adequate customer service levels are maintained, decreases in total inventory investment will immediately yield a higher return on a company's working capital investment.

Companies are increasingly recognizing the opportunity costs of carrying inventory. Dollars invested in inventory could provide a better return, in the long run, invested in new products or new processes to make the company more competitive. Managing inventories is an important part of managing a company. Remember, less is better.

SUMMARY

Basic Questions

Basic questions that need to be asked whenever dealing with inventory:

- What should we stock?
- How should we stock it?
- What's our inventory strategy?
- What are our inventory goals?
- What is the total inventory? What should it be?
- What are the various categories of inventory? What should they be?
- What is the inventory level of each category of inventory? What should it be?
- What is our percentage of inventory accuracy? How can we improve it?
- What is the turnover of each category? What should it be?
- How many days of stock should we have on hand?
- Where are we overstocking? Why? What can be done about it?
- What can we do to improve our total inventory performance?

Symptoms of Poor Inventory Management

- Customer backorders
- Missed ship dates
- Continuously growing inventories, while order input remains constant or decreases
- Lack of adequate storage space
- Uneven production with frequent layoffs and rehirings
- Frequent changes in production runs to meet changing sales requirements
- Excessive machine downtime because of changeover and material shortages
- Widely varying rates of inventory loss or turnover among branch warehouses and production facilities, or widely varying rates of turnover among major inventory items

- Consistently large inventory write-downs because of distress sales, disposal of obsolete or slow-moving items, and so forth
- Consistently large write-downs when physical inventories are taken

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BIOGRAPHY

David Buker is president of the Buker Group located in Orlando, Florida. He provides strategic consulting, mentor consulting, and entrepreneurial consulting to emerging growth companies. He has spent more than 40 years in business management and consulting for major corporations throughout the United States and overseas. In addition, Buker develops and presents management seminars and training programs, which have a strong track record of inspiring managers and improving performance. For many years, he has been an accomplished speaker and keynoter for conferences and conventions worldwide. Buker was the founder, president, and chairman of the board of David W. Buker, Inc., an INC. 500 Company providing education and consulting on manufacturing resource planning, just-in-time, total quality management, and world-class performance throughout the world. He has a bachelor's degree in economics with honors from Wheaton College, and an M.B.A. in finance from the University of Chicago's Executive program.

CHAPTER 10.6

CASE STUDY: LESSONS LEARNED FROM IMPLEMENTING A PAPERLESS WAREHOUSE MANAGEMENT SYSTEM

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Roswell, Georgia

Experiencing growth of about 20 percent per year, an international retailer of fashion merchandise was faced with opening several new distribution centers to support its 1000+ retail stores. While the firm had an existing, homegrown, paperless warehouse management system (WMS) at all of its current facilities, management at the company felt the existing application was very costly to maintain and had several functional shortcomings. The firm decided to investigate more sophisticated off-the-shelf alternatives. The company's stated goal was to select and install a new WMS package in two new facilities in under two years. This case study, which reflects the actual experiences of the authors on a project they were asked to rescue, describes the steps that their client (the retailer) followed to plan, select, and implement this new system. It also provides insight into some of the pitfalls that often accompany these challenging, high-return projects.

BACKGROUND AND SITUATION ANALYSIS: THE STAKEHOLDERS

On every paperless warehouse project there are people who have a major stake in what features are provided by the new system or how the system gets implemented. Anyone who is charged with leading such a project should begin the journey by identifying these people and their central concerns. This will ensure that the project will be allowed to complete and will help identify the issues that could potentially derail the project later. Three major issues and groups drove the scope and objectives of this particular project.

First was the distribution organization. At the time of this case, fashion retail in the United States was a booming business. Fueled by a strong economy and custom-designed lines of apparel, this fashion retailer's sales had almost exhausted the throughput capacity of the firm's existing distribution centers. To escape this problem, the senior vice president of distribution decided that two new facilities would be needed. One facility would be a cross-dock (CD) facility and the other would be a full-featured distribution center (DC) facility.

The cross-dock (CD) facility was to serve as a consolidation point for storebound merchandise coming from overseas manufacturers. The operation was to be of limited scale and complexity. The facility would be 29,000 m^2 (305,000 sq ft) and employ 50 warehouse workers. Furthermore, material processing would be fairly simple and would require employees to do only the following:

- *Receive and inspect* cases of merchandise from overseas manufacturers.
- *Sort* the cases onto pallets bound for certain regions of the country.
- *Store* those cartons for a few days on pallets in pallet rack storage.
- *Pick* all the pallets going to a particular region of the country when they were released.
- *Load* those pallets onto trucks bound for regional pooling points that in turn would sort the cases onto storebound local delivery trucks.

The distribution center (DC), on the other hand, was planned to be much larger and much more complicated. First, it would be a huge facility, covering almost 71,000 m^2 (750,000 sq ft) and employing 600 people. Second, it would support pallet picking, case picking, and piece picking into cartons. Finally, unlike the CD, the DC facility would also require a significant amount of complicated automation. The designers responsible for the building had specified that automated conveyor sortation equipment would be used to deliver cases to each of its 100 dock doors. In summary, the new DC would be a state-of-the-art facility. (See Fig. 10.6.1.)

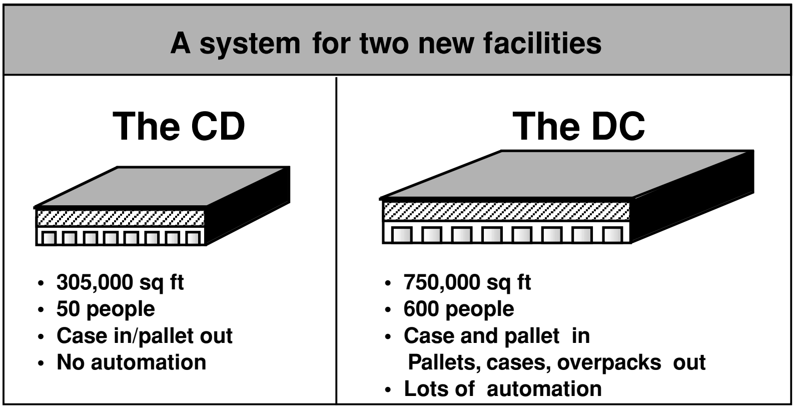

FIGURE 10.6.1 Two new facilities were needed to handle rapidly increasing sales.

While the distribution organization at this firm was trying to solve severe capacity issues, so was the second stakeholder in this system—the retailer's management information systems (MIS) group. Information systems are critical at a retail company. A firm cannot survive unless it is staying on the leading edge of technology; however, at this firm the MIS organization no longer had the resources to both build new strategic information systems and still take care of the aging mainframe applications. Consequently, the vice president of distribution systems was regularly forced to support the new strategic needs of the business by bringing in highly trained and expensive consultants, but this practice was beginning to create a drag on the firm's profitability. He needed to get costs down. His vision for doing this was to replace the old paperless warehouse system (which required nearly eight FTEs to maintain) with a packaged solution that a vendor could keep running for substantially less. This would free up his internal resources to work on projects more strategic to the company.

The third major stakeholder in this project was the industrial engineering organization at the firm. The IE group, charged with reducing operation costs within the firm's many DCs, had recently returned from the annual ScanTech bar coding conference where they had discovered that their homegrown paperless warehouse system was devoid of several valuable modern features. Foremost among these missing features was the *interleaving* of pallet picks and putaways together. This meant that in the current system, forklift drivers could unknowingly put away a pallet near a second pallet that needed to be picked and taken back down to the dock. This information shortage caused extra trips as another driver would be dispatched to pick up that second pallet. This wasted labor and reduced the responsiveness of the distribution center.

Second, the IEs were concerned that the legacy application did not provide for cross-docking pallets. At ScanTech, the retailer's industrial engineers had seen newer systems where, if you needed to ship a pallet of widgets and you had a pallet of widgets on the receiving dock, the system would simply tell you to move the pallet of widgets on the receiving dock to the shipping dock. This was in stark contrast to their existing system, which required the pallet to be put away in storage before it could be brought down to the loading dock. This shortcoming also wasted labor and reduced the responsiveness of a facility.

OBJECTIVES AND SCOPE OF THE PROJECT

The three parties got together in the spring following industrial engineering's trip to ScanTech to set the scope and objectives for the new system. Out of that meeting, it was decided that the new system needed to meet a number of objectives:

- The new software should be finished in time to be tested and installed in the new CD prior to its opening.
- It should leverage the latest in proven technology.
- It should require little in-house support (i.e., the vendor must be able to maintain it).
- The software would be delivered in two phases. In the first phase, the vendor would install software at the less complicated CD. In the second phase, the software would be modified as necessary and installed in the DC.
- After the new software could be demonstrated to work in both the new CD and DC, it would be rolled out to the rest of the firm's distribution centers
- The new system should provide labor-saving features such as cross-docking and interleaving.
- The new system should use a modern, relational database so that information could be easily retrieved from the system for other uses such as management reporting.

PROJECT ORGANIZATION AND HISTORY

After the magnitude of the new system's benefits were established by the industrial engineering department, the company decided to retain a consulting firm to help compose a request for proposal (RFP) for the software as well as quickly pare down the scores of WMS vendors into a reasonable shortlist of qualified candidates. Retaining help in the early stages of a WMS project is generally a good idea, and most companies do it on large projects, but it is important to seek out a consulting firm whose staff is intimately familiar with the WMS industry.

One of the first deliverables that a consulting firm should provide is a road map for getting the system selected and installed. This often will take the form of a Gantt chart that documents the major activities of the project and estimates the start and stop dates for each. For this project, Fig. 10.6.2 shows the various major categories of work that went on and how long it took to complete each activity. You may want to refer to it as you read through the rest of this case.

Composing a Request for Proposal (RFP) for the New System—6 Weeks

Upon their arrival the consultants set up a project structure involving two committees. First was the steering committee composed of the senior VP of distribution, the consulting firm's manager, the IS project manager, the distribution group's project manager (who happened to be an industrial engineer), and the manager of the planned CD facility. The steering committee was responsible for making sure that the project stayed on track, that additional resources were made available when necessary, and that deadlocks between stakeholders were resolved. This group met once per month.

The second group was the joint-application-development (JAD) team. This group was composed of warehouse managers, industrial engineers, and information systems professionals (12 people in total). The JAD group was lead by a joint project management team composed of a project manager from the IS organization and a project manager from the distribution side of the business. Together they drove the team to determine what the system would actually do. The team met two days a week for about a month to flush out the requirements for the new system. This information was taken by the consultants and gradually converted into a request-for-proposal document that was about 80 pages in length. This document described in narrative fashion the flow of product from receiving through shipping as well as the capabilities needed for functions such as inventory management (e.g., cycle counting), the connection between the WMS and the retailer's order management host software, and wave-pick planning.

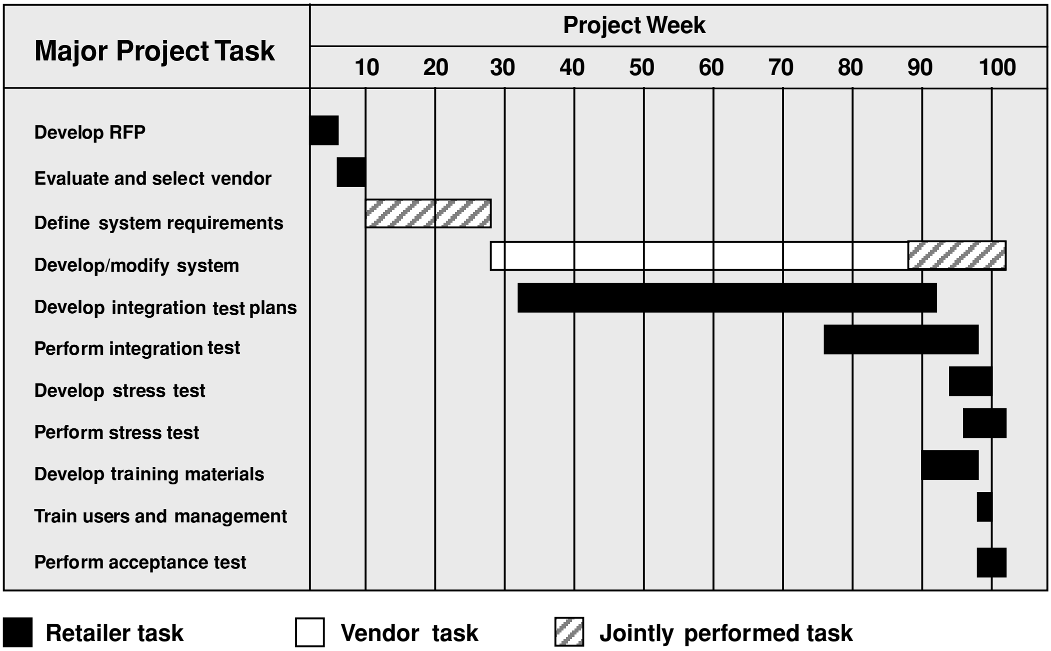

FIGURE 10.6.2 Gantt chart for the CD facility WMS design and implementation.

It is particularly important that industrial engineers (IEs) take an extremely active role in the development of the RFP. Oftentimes the JAD sessions are excellent forums to discuss more efficient ways of doing things as well as a means of getting commitment from others to implement such changes. For this reason it is a good idea *not* to limit the scope of these discussions with the assumption that the same material handling processes and equipment, storage modes, and/or layout will be used. Many times, WMS projects fail to generate a proper return because firms are simply looking to automate what they do today. This often severely limits the payback of a new paperless warehouse system. It is the IE's job to prevent this from happening.

It is also the IE's job (oftentimes working with consultants) to assess the worthiness of new features suggested by the users in these meetings. When a new system is being planned, it occasionally happens that users will introduce lots of makes-my-life-easier requirements—especially if they have an existing system. While you have to include some of these just to get the buy-in necessary to install the system, a good project manager/IE will watch to make sure that this behavior doesn't get out of hand. Furthermore, it is important in the RFP that he or she distinguish between the mandatory functionality that the system must possess and the optional "nice-to-haves," because every added report, screen, and so forth will delay those features that the "shareholders" really want installed.

A good lesson learned from this project is the importance of *sharing the responsibility and hence the leadership for the project between the user organization and the information systems group.* Too often, the IS department is charged with the implementation of these systems on its own. This can create an adversarial relationship between the two organizations whereby the following occurs:

- The users assume no responsibility for the delivery date of the system and demand all kinds of enhancements that have minimal payback but that they claim they cannot live without.
- The IS organization's ownership in the system's quality or ease of use is minimal, leading to functionality being delivered by the vendor that either doesn't do what it's supposed to do or is very difficult to use.

Both of these problems can cause a project to drag on indefinitely, but both can be mitigated by having a two-person project management team. To get an idea of just how far the sharing of responsibility went in this case study, by the end of this project the user's project manager was

- Telling programmers how to generally fix various bugs in reports, screens, and the putaway algorithm.
- Debating with the CD manager over what constituted functionality that was *really* needed.
- Demanding that the director of IS responsible for the project contribute more and better resources to the project.

Selecting a WMS Vendor—3 Weeks

At the end of week 5, the RFP was sent out. Most vendors took a week or less to prepare their responses, because they were warned ahead of time. The sixth and seventh weeks of the project were spent reviewing the responses and culling the candidates to a shortlist of three. These remaining candidates were asked to come in to make presentations and demonstrate their software. The JAD team members were invited to all of these presentations and given a scoring system for evaluating the fit of each vendor's package. The scorecard was to be filled out at the end of each vendor's demonstration.

Scoring Vendor Demonstrations. The first vendor's package appeared more sophisticated and advanced than the other two. It had a graphical user interface, was very configurable, and was built on top of a relational database. However, it also was totally unproven. The vendor's reps explained that they had just finished coding this new version of their package and were looking for someone to partner with to refine and test the system. While this vendor had a long history of selling reliable systems, it was no longer selling its old package. Its new system was not installed anywhere, and the added functionality would raise the cost to close to $1 million to license it for both new sites. The vendor's reps also remarked at the end of their demo that they were not willing to commit to a firm fixed price until they had had an opportunity to define the requirements for the system exactly, a process that would take three months. (This is fairly typical of most WMS vendor proposals for large systems.)

The second vendor had a less sophisticated, character-based system, but claimed it was working on a more user-friendly GUI system. On paper, the reps showed what appeared to be a few installations of comparable complexity to the planned DC. They also estimated in their response to the RFP that their package would cost between $500,000 and $750,000—significantly less than the other two, but they too were unwilling to commit to a firm fixed price until after a requirements definition phase was completed. Regardless, their demo went poorly, and the scores they were given by the JAD team were so low that the vendor was eliminated from the contest.

The third candidate's application was not quite as user-friendly, and it used old, unacceptable database technology, but its reps proposed a different approach for implementing their system. They offered to assemble pieces from past projects into a custom application tailored *exactly* to the customer's needs for what they estimated in their response to the RFP would be close to $750,000, or roughly the same as their competition's packaged, partially configurable software. This vendor also offered to convert its application to use the relational database that the retailer favored as opposed to the current database it supported.

These advantages made the package look like the favorite until the vendor admitted that at the time it would be hard pressed to provide the resources for the project needed to achieve the CD facility's opening date. This was a big problem. The new CD facility had to have a system to operate. While the retailer had a concurrent project under way to migrate the legacy application to the CD facility, everyone wanted to cancel the project and use the money being spent on contractors and in-house programming staff for other purposes. For this reason, it appeared that the resource shortage might eliminate the vendor from the running, but then the consulting firm assisting the retailer in the selection of a qualified vendor did something surprising. The consulting firm, which was working on a separate project with this same vendor at a different client site, proposed that *it* would provide development staff needed to help the vendor deliver the project in time for the opening of the new CD facility. This helped bolster the vendor's candidacy significantly and kept it in the running.

Checking References. After the presentations were finished, during the eighth week of the project, the project managers and the future CD manager began making phone calls to references supplied by each vendor. Since the first candidate was selling a brand-new version of its software, the references were clients who used the firm's older code at sites roughly comparable in complexity to the retailer's planned DC site. The third candidate's references were a hodgepodge, but because the retailer ended up selecting this vendor, it's important to review the results of these phone calls:

- The first reference was an operations manager for a specialty retailer who had installed the vendor's Location Management System close to 10 years earlier. This application was really the *grandfather* of the application currently being proposed by the vendor. It ran on a different platform, and it was also something less than a WMS. It didn't support interleaving, cross-docking, or directed putaway. The facility also had no sophisticated automation that the software needed to control. In summary, the application was more or less a computerized card file that the specialty retailer used to record where items were stored in the warehouse. According to the operations manager, this project took the vendor about a year to complete, and it was delivered on time. What was important was that this application used a relational database that the fashion retailer was interested in using.

- The second reference was an operations manager at a catalog retailer that was one of the vendor's very first WMS customers. This customer had installed the system that was the predecessor of the system being sold to the fashion retailer. It ran on a different kind of computer and used a totally different database. The facility was, however, roughly comparable in complexity to the planned DC. When asked to critique the vendor's project management skills, the customer mentioned that the vendor seemed light on project management, but the system went in well. He went on to suggest that since this was one of the early sites, the vendor used many of the original staff who wrote the bulk of the core code to perform this installation.
- The third reference was the VP of warehousing and distribution for a manufacturer and retailer of fine dress shirts. This customer was installing the *new version* of the vendor's code, but it was not yet operational. The VP gave the vendor a grade of B so far. Phase I, the inbound piece and putaway, was moving along a little behind schedule, but was making progress.
- The fourth reference was actually not submitted by the vendor. Instead, the fashion retailer had discovered using the consulting firm that a major music retailer was installing this same system. This system also was in the early phases of being constructed when the customer's project manager at the site was contacted. At the time, he remarked that they were happy for the most part with how the project had proceeded so far, but recently they had started haggling with the vendor to obtain enough qualified resources to complete the project.

After the presentations were complete and the references checked, the negotiations got serious. The prices, not too surprisingly, went up as the vendors claimed that the functionality being requested was substantially more than their average client site. The first vendor changed its bid to $2 million, the second to $1 million, and the third to $1.4 million. None of these bids included any hardware costs, because the retailer believed it could buy all such equipment on its own for less than any of the vendors could purchase it. These bids also did not include the cost of integrating the radio-frequency (RF) terminals at the CD with the system or installing the software on the retailer's machine. These responsibilities were to remain the customer's.

A meeting of the project steering committee was held to decide whether the first or third vendor would get the job. It was decided that there was too much risk associated with the first vendor because of its new, untried system. Also, this vendor was more expensive and already had admitted that it couldn't hit the opening date of the planned CD facility. Consequently, in the ninth week of the project, the committee awarded the contract to the third vendor, who supposedly had a package ready to piece together and install for a much lower price.

Lessons Learned from the Selection Experience. In hindsight, there are several lessons to be collected from this part of the project. First of all, the fashion retailer should have required that the vendor that looked most favorable conduct a "conference room pilot" of its system, walking through the more significant requirements in the RFP as opposed to giving only a general demo of its product. This would have clarified the functionality that the packages actually possessed and the gap between the users needs and the package. The firm also may have gotten a glimpse of how unstable the code was.

Second, the process of doing reference checks was really very shallow. They were done by phone, which limited the number of people who could be questioned to one or two. Experience shows that people are willing to give you more information face-to-face than by telephone. Another problem with these reference checks was that the retailer got only one perspective on each project. Furthermore, the last reference wasn't even the person who had the closest working relationship with the vendor.

Third, everyone chose to ignore the warning signals sent by the reference checks. People who do this type of work regularly become alarmed when there are no glowing references. If a firm has 40 or 50 installations and cannot find a customer who will just rave about its work, look out. The other vendors managed to do this, why didn't the third vendor? The data collected from the first two reference checks regarding the delivery and quality of this vendor's current product are of very little value. The first site isn't even close to being comparable in complexity to the fashion retailer's planned DC site, and neither of these sites uses the software that the fashion retailer is going to purchase. The new software runs on a completely different make of machine and operating system, which makes it significantly different from previous versions. The third and fourth references hardly made the project team feel any more comfortable. Both suggested that the new system was not yet installed and working anywhere. Furthermore, both these references seemed to suggest that the vendor was having a problem supplying qualified people to deliver its existing projects.

Fourth, the fashion retailer failed to find out the most important piece of information about vendor 3 in its reference checks. To understand what was overlooked, consider the fact that there tend to be two kinds of WMS vendors operating in the marketplace. The first group has feature-rich WMS packages targeted usually at two to four industry segments. This group usually sells its packages with few or no modifications, as proposed by vendors 1 and 2 on this project. A second, larger group of vendors will piece together a more or less custom application from past engagements or customers. With both groups, it is critical that you determine if there really is a good fit between your needs and their package. With the second group, however, it is just as critical to determine if the people who are going to work on your project and the processes they are going to follow have some likelihood of ensuring the quality of the project. This was overlooked, and it nearly doomed the effort.

Defining the Requirements for the New System—18 weeks

At the end of week 9, the contract was awarded to the third vendor. The following week, the vendor's design team showed up to begin the requirements definition phase of the project. The result of this effort was the creation of two documents that would be used by programmers to piece together and customize the retailer's system:

- A *functional design specification* (FDS), similar to the RFP that was sent out (only it would be more detailed and attempt to link the requirements of the retailer to existing functions and features of the vendor's code set)
- A *user interface specification* (UIS), describing the screens and their functionality from a user perspective

The requirements definition phase was conducted much like the JAD sessions in that a committee, composed mostly of the same people who evaluated the proposals, was led by the vendor's process designer and the consultants through a process to determine what the system needed to do. The consultants were retained to help make sure that the design intent captured in the RFP was transferred successfully to the vendor and to act as a catalyst for getting things done on the retailer's side of the project.

Almost out of the gate, the vendor appeared to have a personnel problem as the design team was led by the salesman responsible for the account, not by an operations process designer. Furthermore, the design team would work only two to three days every other week. Weeks went by and little progress was made. The retailer felt no more at ease when, during week 15, the vendor's design team was augmented with a full-time operations process designer. While this new employee seemed very knowledgeable about warehousing, he seemed to know little about the vendor's software.

The requirements definition process struggled on for another four weeks before the fashion retailer, frustrated that little progress had been made, finally issued an ultimatum. The project manager told the vendor that it needed to commit to getting this work done in a timely fashion or the client would take its business elsewhere. This crisis resulted in the president of the software firm showing up to help get the project back on track.

Two weeks later the fashion retailer faced another important decision. The new CD facility was scheduled to open in less than six months, and the requirements process showed no sign of being over soon. As a result, the steering committee decided to keep funding an entirely separate project team that focused on preparing the existing legacy system to work at the new CD site. This was going to cost the retailer over a $100,000, but it appeared worth it in order to guarantee that some system was available when the CD opened.

By the end of the twenty-eighth week, the UIS and FDS were finally completed. The vendor also increased the price of the software by $200,000, to $1.6 million, based on its new understanding of the scope. The contract was also finalized to award the vendor an additional $130,000 and $180,000 as a performance bonus if it achieved its CD and DC target dates. The retailer also insisted that a penalty clause be included in the contract that would subtract $1000 per day and $6000 per day from those bonus amounts for each day the vendor was late.

Lessons Learned from the Requirements Definition Phase. Several important lessons were revealed during this experience. *Don't ignore the early warning signs on these projects.* If a project starts out poorly, it is a good sign that things will continue that way. Furthermore, keep in mind that once the construction and coding of the system has begun, it is very hard to fire a vendor and switch horses because of the immense emotional and financial investment already made. Furthermore, to do so might be considered a career-limiting decision. On this project, there were so many subtle warning signs early on in the project that to dismiss them after the start of coding would have had immense career implications for most of the MIS staff. *Remember that it is much easier to walk away sooner rather than later.*

Second, *don't bet a new facility on a virgin system.* As was hinted at earlier, this software had never been installed anyplace and made to work right. Consequently, it might be called a *virgin system.* It is not a good idea to install a virgin system or any system involving huge amounts of coding and integration work (more than 1200 person-hours of programming effort) in a new facility that has no legacy application to fall back on if something goes wrong. The fashion retailer made the right decision to invest in its legacy application to ensure that some system was available at the CD on opening day.

Implementing the Warehouse Management System. After the requirements for the new system were solid, the project split into two groups: the client side of the project and the vendor side of the project. The vendor went off to its headquarters to put together a detailed design for the system as well as to customize and integrate various pieces of code from other past projects into a new set of code that would meet the retailer's needs. The retailer went off to develop a series of tests that could be used to make sure that the software, when it was delivered, satisfied the firm's needs and worked properly.

Developing the Paperless Warehouse Management System—71 Weeks

Because of holidays and other customer commitments, the vendor's development effort did not really begin until 33 weeks after the steering committee had commissioned the project. Following the requirements definition phase, the vendor estimated that, using seven full-time people to customize and integrate the code, it should take the firm 30 weeks to deliver the software. At the time, the projection seemed aggressive but possible. Unfortunately, the vendor never was able to staff the project as planned. Figure 10.6.3 documents the number of staff that actually worked on the project during this period.

Per the contract, in week 40 one of the retailer's programming staff was loaned to the vendor's development group. Soon after arriving, this person began sending back less-than-flattering reports about the vendor. First, it appeared that the vendor had little in terms of a detailed design to help programmers code the project. Second, the code was particularly complicated and only one person on this project was actually familiar with it. Third, there was no one yet hired to unit-test the application as the programmers finished pieces of the new system. But the worst piece of news was that the vendor was losing programmers at a very rapid pace.

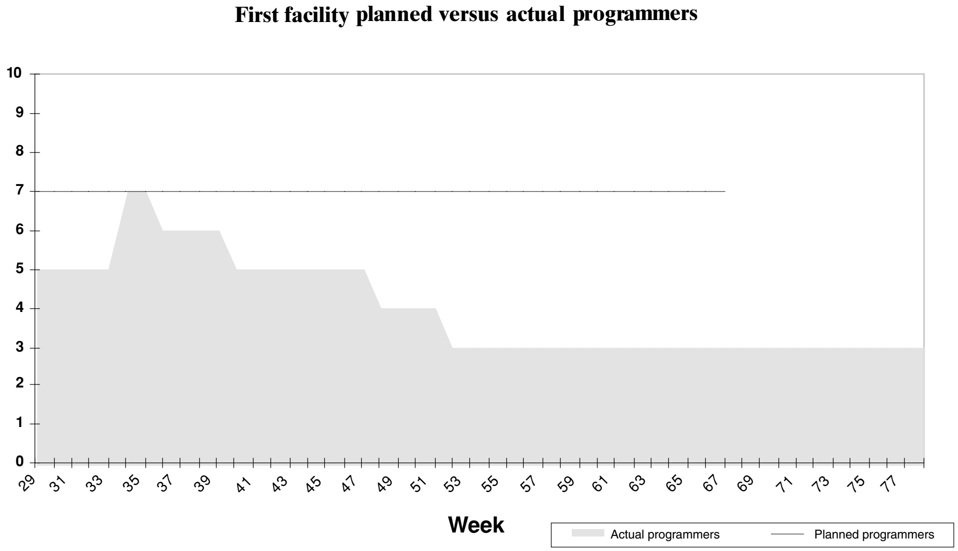

FIGURE 10.6.3 There was a shortage of programmers on this project.

According to the retailer's on-site programmer, the vendor wasn't staffing the project anywhere close to the level originally forecasted. This resource shortage was mostly caused by turnover in the vendor's development team. The vendor had elected to use a few full-time people supplemented by contract programmers supplied by the consulting firm. Because of the working conditions, the rate of pay, and other reasons, all of the full-time people left, including eventually the technical lead for the project. Things got worse when the relationship between the consulting firm and the vendor fell apart. This resulted in the vendor staffing the project with only three inexperienced contractors, all of whom had no prior knowledge of the vendor's software. *It is fairly clear that the resource problem more than any other issue caused this project to drag on much longer than it should have.*

Because of the programmer's report, another member of the retailer's staff was dispatched in week 46 to help unit-test the application. Two weeks later, the vendor hired a new person to perform this work as well, but the retailer elected to keep its quality control person on-site just to help out.

Week 63 arrived and the vendor missed the CD's delivery date. Members of the retailer's MIS staff, who had been sent to participate in the development, reported that the code was nowhere near ready to be installed and acceptance-tested. Ten more weeks went by, and the retailer's senior management decided to bring in a *new* consulting firm (the authors' firm) to manage all the activities the retailer needed to accomplish before the new system arrived. Additionally, it was the new consulting firm's job to perform regular assessments of the vendor's progress.

Finally, in week 76, the first installment of the vendor's code arrived for testing at the retailer's site. However, it took the retailer three weeks to figure out how to compile and run this software on its hardware. This glitch was caused by differences between the development environments of the vendor and the retailer. Still, even after resolving these problems, the system seemed terribly unstable, which made any mass testing of the system almost impossible. To add to everyone's concern, the retailer's team could not seem to get the RF units to work with the new system. When the vendor's reps were questioned about this problem, they washed their hands of the issue and claimed that it was a hardware, not a software, problem.

With all these problems and the vendor's poor performance undeniable at that point, rumors began to circulate suggesting that the system would never be delivered.

By week 85, little progress had been made on testing the software. The application was still just too unstable to test much functionality. At the request of the consulting firm, a bounds-checker software package was used to identify memory leaks in the vendor's code. The retailer's project team was doubly shocked by the findings this tool revealed and by the announcement in that same week that the vendor's most experienced programmer on the project had resigned. These two facts, combined with the vendor's poor past performance, forced the retailer to draw up plans for taking over the project entirely.

The first part of this plan was to insist that the vendor move the development team on-site. After much haggling, the vendor reluctantly agreed to this as long as the customer paid the travel expenses. This was not an inexpensive decision, but it put the vendor's programmers in a position where they could be monitored daily to make sure they weren't being dragged off to work on other projects (a very real risk at the time), and it also made these programmers accessible to the retailer's own programming staff for questions. Finally, there was also a concern that the vendor's staff members were working on postimplementation issues rather than start-up bugs just to keep the overall bug count down. With the vendor's programmers on-site, the client could make sure that they were working on the most important bugs.

The second part of this plan involved bringing on four contract programmers to work on the *retailer's side of the project* starting in week 87. These programmers were initially responsible for coding fixes to all of the memory leaks in the vendor's code. It was hoped that once this work was completed the code would become more stable and the programmers would also know enough to take over all of the remaining coding tasks from the vendor if it was still deemed necessary to do so.

By week 88, the code began to shape up on the inbound side. Testing now swung into high gear. With momentum building, project management felt comfortable enough to advertise a no-excuses go-live date 12 weeks away. The steering committee started meeting weekly to discuss project progress as well as to eliminate any last-minute roadblocks. Unexpectedly, the project received a most welcome boost when the vendor contributed four experienced programmers from another project to the effort. From that point forward, events proceeded at a brisk pace. Week 100's start date was missed, but the system went live at the start of week 102—nine months later than the original date promised by the vendor.

Lessons Learned from the Development Phase. There are several important lessons to be culled from this part of the project's history. *First, insist that someone from your development organization be integrated into the vendor's development team at the beginning of the coding effort.* This person can reduce your risk if the vendor is unable to deliver the project and can be used to train other staff if need be. This person will be an invaluable source of information regarding how solid the code *really* is throughout the project. Also, he or she can provide feedback early on about the development methodology being followed, the capabilities of the vendor's staff, and so forth. The key is to act on this information, however. In this case, the retailer just ignored the reports until it was almost too late.

The second lesson is let the vendor perform all of the device integration work. In the first facility there was little automation with which the vendor's application needed to communicate, but there were RF units that needed to work with the system. Because the complexity of this equipment seemed low, the retailer felt it could handle the integration of this equipment. Unfortunately, this led to a situation where the RF software provider, the RF hardware provider, and the WMS vendor all claimed it was the other firm's problem when the retailer's existing RF units did not work with the new system. This took the customer nearly two months to sort out, which could have delayed the project if the software development effort had not been so far behind. It is a good idea to let the vendor do this work. This is especially true on projects involving lots of complicated automation such as conveyor sortation equipment.

The third tactic worth remembering is that getting the vendor on-site is costly, but if you are worried that your vendor is working on other customer projects or is not working on what's *important, you almost have to do it.* This project was unusual, and 9 out of 10 projects may not require you to take this step. Keep in mind that it costs about $15 per programming hour to bring a vendor programmer on-site. If you compare $15 per person-hour to the $50 to $75 per person-hour rate that a new contractor will cost if you have to take over the project to do the same work, then this doesn't seem like such a bad alternative.

There is an old adage about software development that says, "Adding more programmers to a late project only makes the project later." Oftentimes this is true, but *sometimes adding programmers to a late project doesn't really make it later, as the customer discovered in this situation.* There was a lot of concern on the vendor's part that the programmers the customer was contributing to the effort would set back the more experienced programmers on the project, but this didn't happen. Most likely, it didn't happen because the tasks that the retailer's programming staff were given to complete were fairly simple. Furthermore, the programmers on the vendor's side of the project were fairly inexperienced themselves. There was not much to be gained from asking them deep questions about the inner workings of the code. Everyone was pretty much starting from scratch in that area, and thus the productivity-dampening effect never manifested itself. There is no doubt in anyone's mind that this tactic resulted in the software coming in much sooner.

Developing the Test Plans and Testing the Application

In week 28, when the vendor left the retailer's site to code the application, the retailer formed a team of individuals who were responsible for testing the system once it was completed.* This group, known as the *test team,* was organized as depicted in Fig. 10.6.4.

In large paperless warehouse systems involving lots of customization like the one in this case study, there are usually several different tests that the customer will want to conduct to ensure that the software delivered by the vendor works properly. Because of the complexity and sheer amount of testing that needs to take place, most project managers require that these tests be prepared and written down in advance. Two documents typically are required: a *test plan,* which states the goal behind each major test scenario, and *test scripts,* which are the actual tests described in such detail that a novice user could step through the application to conduct them. (See Fig. 10.6.5 for an example.)

On this project, test scripts were written for the smoke test, the integration test, the stress test, and the acceptance test. This was quite a large effort involving four full-time people for more than a year and nine or so part-time people off and on during that period. All together, this work accounted for close to 10,000 person-hours of effort, the bulk of which were related to the integration test.

Developing the Integration Test. An integration test is used to make sure that the new system works in realistic business situations once it is installed and attached to all of the other computer systems that feed or rely on information from the application. Oftentimes, the integration test is conducted by the MIS organization to establish whether the system works correctly before it is handed over to the users to run their acceptance test. The integration test, therefore, tries to exercise most of the functionality within the package and all of the functionality that would be used during a typical cycle of business. It is also executed on the actual machine that will be used to run the facility. This test will require live connections to the other external systems with which the paperless warehouse management system will interface on a day-to-day basis (e.g., order entry and inventory management).

The development of the integration test scenarios is another part of these projects in which industrial engineers should be very active. Oftentimes, they know the requirements for the

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* The previous section described the completion of this project from the vendor's side of this project. This section describes what happened from the client's side of the project. Both occurred simultaneously.

CASE STUDY: LESSONS LEARNED FROM IMPLEMENTING A PAPERLESS WAREHOUSE MANAGEMENT SYSTEM

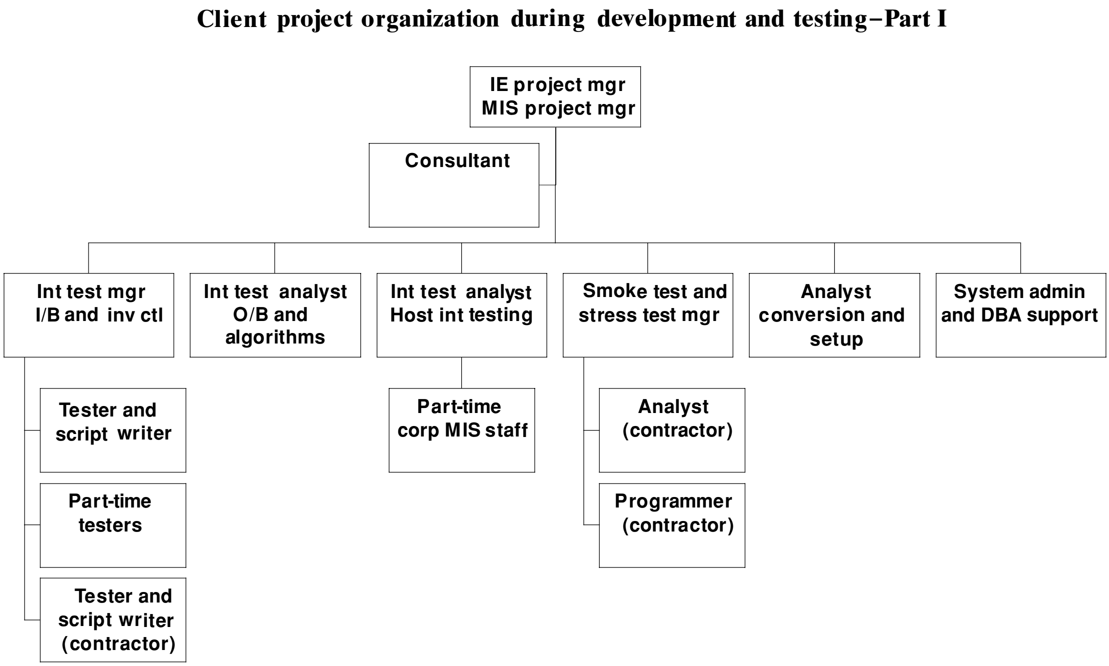

Client project organization during development and testing–Part I
IE project mgr
MIS project mgr
Consultant
Int test mgr I/B and inv ctl
Int test analyst O/B and algorithms
Int test analyst Host int testing
Smoke test and stress test mgr
Analyst conversion and setup
System admin and DBA support
Tester and script writer
Part-time testers
Tester and script writer (contractor)
Part-time corp MIS staff
Analyst (contractor)
Programmer (contractor)

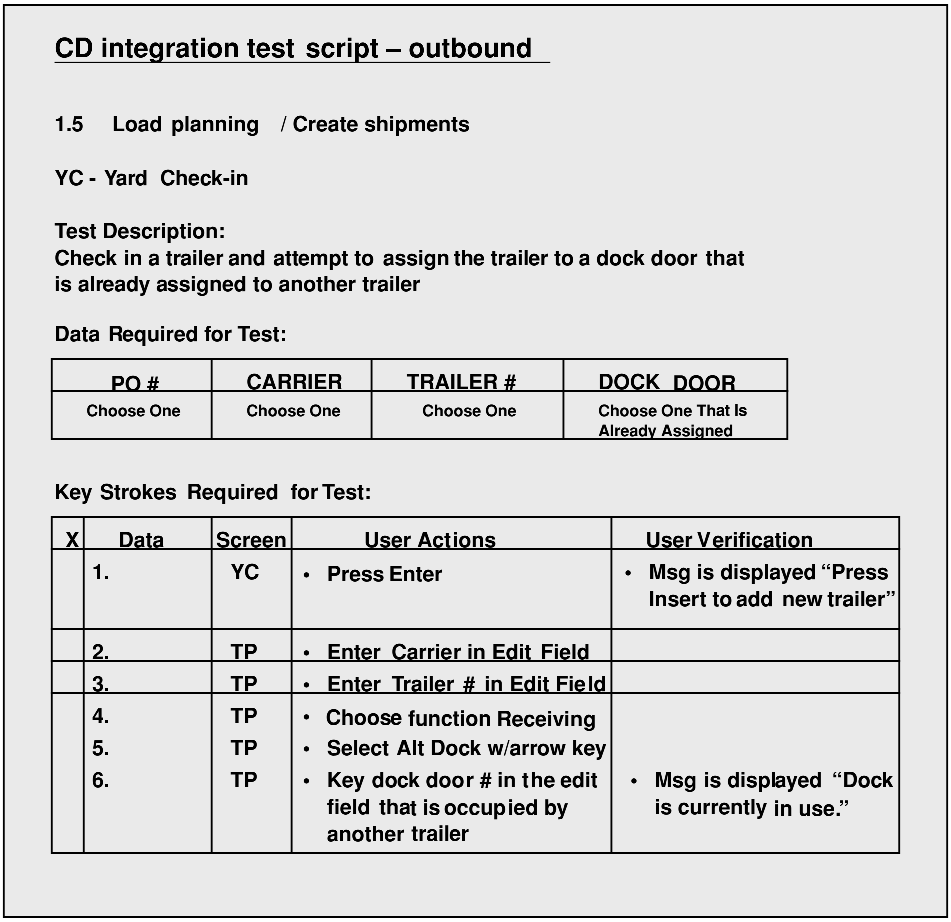
FIGURE 10.6.4 The retailer's test team organizational structure.

new system better than the people charged with developing the tests. They should review the work of the test team to ensure that it is complete and accurate.

For the CD facility, the integration test was divided up into five different areas: inbound functionality, outbound functionality, host interface functionality, algorithms, and inventory control/miscellaneous functionality. The host interface test scripts checked to make sure that the WMS generated all of the uploads it was supposed to *when* it was supposed to. It also made sure that downloads from host systems such as the purchase order system were processed correctly. The algorithms part of the test focused on making sure that two critical pieces of the package worked correctly: (1) The system's putaway algorithm properly determined where a newly received pallet needed to be stored, and (2) the system's work-queue management algorithm served each RF user in the warehouse with the next most appropriate task. The inventory control/miscellaneous portion of the test exercised and evaluated the cycle-counting features, reports, inquiry screens, and so forth associated with the system.

The development of the integration test began almost immediately after the requirements definition process was complete in week 30. This work took quite a while to complete because at the beginning of the process little was available in terms of documentation from the vendor about how the system worked. *A lesson learned is to try to get as much information about the vendor's system up front as possible.* This might require that you get documentation from other customers of the vendor, but the more you can get the faster this work can proceed.

The hope on this project was to run through pieces of the integration test as the software arrived piece by piece. In this way, it was thought that bugs could be flushed out quicker and submitted for fixes earlier, thus shortening the project. Unfortunately, the code did not come together as well as had been hoped. When the inbound code first arrived in week 76, the test team attempted to start the inbound part of the integration test and quickly discovered that the code was so unstable that it was foolish to try to do this. It just made no sense to run several days' worth of inbound activity through the new WMS (as the integration test called for)



CD integration test script – outbound

1.5 Load planning / Create shipments

YC - Yard Check-in

Test Description:
Check in a trailer and attempt to assign the trailer to a dock door that is already assigned to another trailer

Data Required for Test:

PO #	CARRIER	TRAILER #	DOCK DOOR
Choose One	Choose One	Choose One	Choose One That Is Already Assigned

Key Strokes Required for Test:

X	Data	Screen	User Actions	User Verification
	1.	YC	• Press Enter	• Msg is displayed "Press Insert to add new trailer"
	2.	TP	• Enter Carrier in Edit Field	
	3.	TP	• Enter Trailer # in Edit Field	
	4.	TP	• Choose function Receiving	
	5.	TP	• Select Alt Dock w/arrow key	
	6.	TP	• Key dock door # in the edit field that is occupied by another trailer	• Msg is displayed "Dock is currently in use."

FIGURE 10.6.5 A sample test script for outbound functionality.

when the system couldn't process a single inbound trailer without crashing. After this experience, the team changed the testing approach.

Starting in week 80, the test team began system-testing the code for the vendor. This involved using a little bit of data just to flush out which screens were working and which were not. We would attempt to make sure that the core of receiving worked (as opposed to testing every possible situation, as we might during the integration test). It is important to point out that the vendor on most projects typically performs this systems testing work. On this project, however, the quality was so poor it was evident that the project would be dragged on for quite a while if the test team didn't help identify the major bugs in the code for the vendor *prior to* beginning the integration test. In order to keep everyone productive, a formal process was set up to do this.

Smoke and System Testing. Often, the productivity of the test staff on a project is overlooked. Programmers usually get the bulk of the attention; however, a project cannot be completed unless all the bugs in the code can be identified quickly. In order to avoid the situation in which a new version of the code would be installed and then crash—thus preventing any testing of the software (or, worse yet, training)—the test team set up a series of quarantine areas that new code would pass through before being submitted to the integration testers, the acceptance testers, or the people training on the system. Each of these quarantine areas was essentially a separate warehouse running a different version of the code. If the code passed the bulk of the tests in a given environment, it was allowed to move on. If it didn't, the code remained in that quarantine area until it was replaced by the next version of the code. Figure 10.6.6 documents this flow.

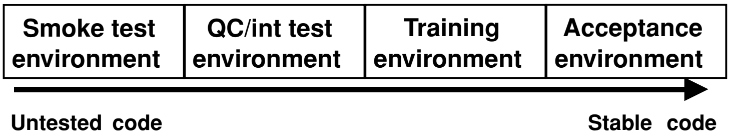


FIGURE 10.6.6 Flow of code through testing.

The process worked as follows. When a new version of the code would arrive, it would first be installed in the smoke test environment, where it would be subjected to a four-hour test of very basic functionality (receive a carton, put away a pallet, release orders for picking, pick pallet, load pallet, etc.). If the code passed these basic tests, testers would be told that QC considered the code stable enough. The e-mail sent by the project manager listing what bugs had been fixed in the latest version of the code would then be checked by a tester to confirm that those bugs had actually been fixed. After "QCing" these fixes,* the tester would explore their specialty area (e.g., inbound, outbound, inventory control) to see if anything else was broken. Bugs would be documented on a bug sheet like the one shown in Fig. 10.6.7. This sheet would be turned in to the project manager to be tracked and communicated back to the vendor the next day.

Performing the Integration Test. System and QC testing went on from week 76 until about week 90, when the code was finally stabilized well enough to begin the true integration testing effort. Once the code was somewhat stable, it didn't take long for these tests to be run. This testing did, however, still show signs of some instability as well as some major remaining bugs. As these issues were remedied, the barrier to going live became less technical and more psychological.

One of the greatest challenges faced during this phase of the effort was not just finding and eliminating all of the showstopper bugs, it was *convincing* everyone that it had been done. By this stage of the project there were close to 15 people (not counting the vendor's staff) looking at the code almost daily. Some of these people were well experienced with the system and understood how it worked, but more were not. Naturally, this resulted in people finding fault with the system when the problem was not the system but how people were using it, which was only made worse when the experienced staff was unable to investigate and explain away all the issues that the new people were discovering. Some were obviously instances of the software being misused, but many of the problems the experienced staff couldn't even reproduce. Unfortunately, the inability of experienced project team members to reproduce such bugs didn't make them any less significant to the users and testers who had discovered them.

To combat this situation, project management began announcing by e-mail whenever a reported bug could not be reproduced and was being deleted from the bug list. This kept the bug count down so that it would more adequately reflect how close the software was to being finished, and it also gave everyone the chance to appeal the decision. Second, the steering

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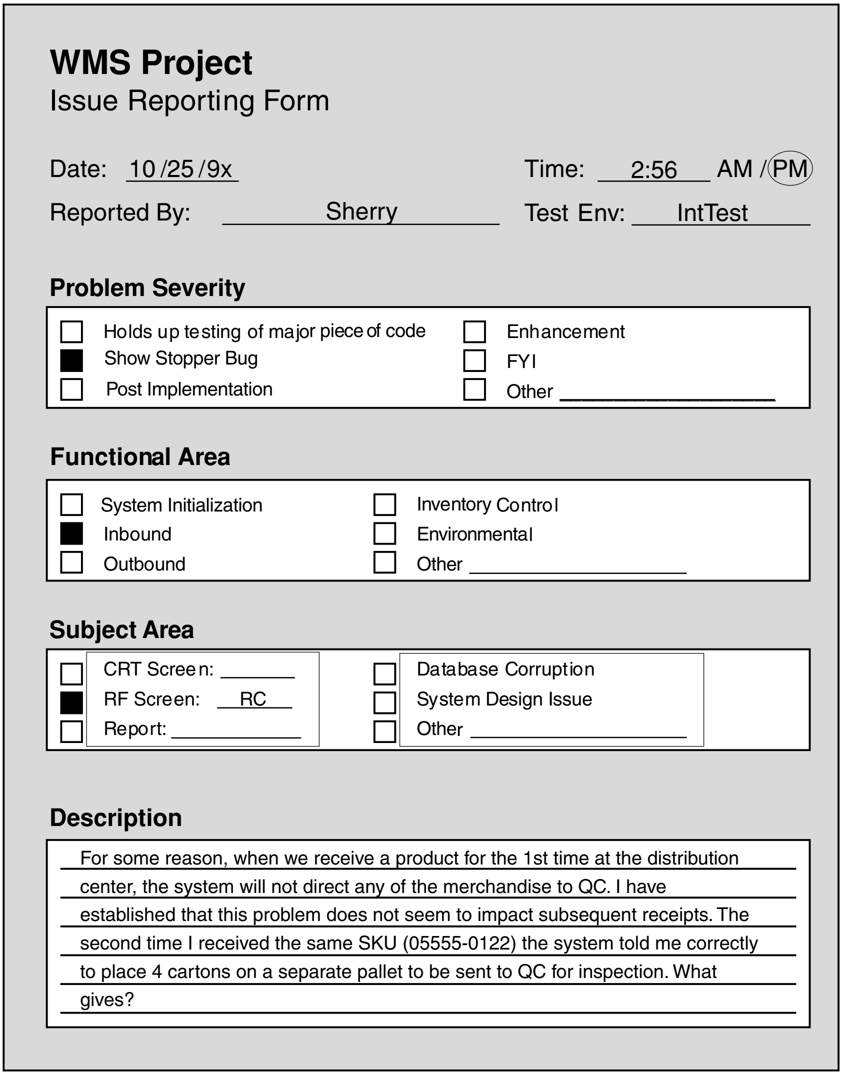
* We referred to checking bug fixes as *QC testing*.



WMS Project
Issue Reporting Form

Date: 10/25/9x
Time: 2:56 AM / [✓ PM]
Reported By: Sherry
Test Env: IntTest

Problem Severity

☐ Holds up testing of major piece of code
☒ Show Stopper Bug
☐ Post Implementation
☐ Enhancement
☐ FYI
☐ Other ____________________

Functional Area

☐ System Initialization
☒ Inbound
☐ Outbound
☐ Inventory Control
☐ Environmental
☐ Other ____________________

Subject Area

☐ CRT Screen: _______
☒ RF Screen: RC
☐ Report: ____________
☐ Database Corruption
☐ System Design Issue
☐ Other ____________________

Description

For some reason, when we receive a product for the 1st time at the distribution center, the system will not direct any of the merchandise to QC. I have established that this problem does not seem to impact subsequent receipts. The second time I received the same SKU (05555-0122) the system told me correctly to place 4 cartons on a separate pallet to be sent to QC for inspection. What gives?

FIGURE 10.6.7 Sample bug sheet.

committee began reviewing the bug list each week, stepping through the showstoppers one by one. In this way, the major players could debate any questionable issues that remained. This also kept postimplementation issues from sneaking onto the showstopper list.

Finally, senior management together with project management set week 101 as the drop-dead date. This helped focus the team. It sent the message that management felt the code was nearing success and that they weren't prepared to test forever to achieve a totally bulletproof product. They understood there would be some problems at start-up; there always are.

Senior management further curbed the affinity for generating showstoppers by offering guidelines for what constituted a real showstopper. The vice president responsible for the CD facility stated that any bug that would severely impact inventory accuracy or the throughput of the facility would be classified as a showstopper. All others could be debated, but each had to be shown to be just as damaging to the operation to get on the list. Although not everyone was perfectly comfortable on the day we went live, most found that these measures helped spread the risk to the point where it was worth giving the system a try.

Developing the Training Materials and Training the Employees. Training is often offered as an extra service by WMS software providers, but because the fashion retailer had its own training department within the distribution organization, it decided to keep the training in-house. To better organize the effort, however, the retailer asked a consultant experienced in WMS training to come in and set up a work plan for getting the work done. This consultant was also used later in the process to review the training materials.

The creation of the training materials actually began with the development of user procedures for the system. Soon after the first pieces of code arrived at the retailer, a technical writer was charged with developing procedures for how the system would be used to perform all of the basic tasks required in the new CD facility. This effort took roughly three months (of half-time work) to complete.

Once the user procedures were done and the code stabilized, four senior warehouse employees were selected to learn the system, develop training materials for it, and train the rest of the users in the use of the application. Starting in week 89, this group spent two weeks training on the system and learning how to use PowerPoint and other Microsoft Office products to develop the materials. With knowledge of these tools plus the application itself, the training team then spent four more weeks of full-time work to actually develop the training materials.

The training materials and related courses were organized into five sections: inbound, outbound, clerical, management, and environmental. The inbound course covered all activities that would be performed by employees responsible for unloading trailers and putting away pallets. The outbound course taught people how to pick pallets out of storage and scan cases and pallets onto an outbound trailer. The clerical course covered all the office activities that have to go on before and after a trailer is loaded or unloaded. This course also explained how inbound trailers would be checked into the system, how receipt information would be uploaded to the host, how outbound trailers would be set up to cause work tasks to be released to the floor, and how bills of lading would be printed. The management course covered tasks such as inbound and outbound forecasting, setting up inventory cycle counts, and so forth. Finally, the environmental course covered all the screens used to set up the system.

Before the end users were trained in the system, the trainers trained the management personnel at the CD facility to obtain feedback on the course materials and lesson plans. Management training lasted a week and was completed in week 95 of the project. The training team then used the feedback from the managers to refine the courses and presented the enhanced materials to the rest of the CD's staff a week later. By week 101, end-user training was complete.

Developing and Performing the Stress Test. Before a new system is installed, not only should that system perform each receiving, putaway, picking, and loading task properly, it should also perform these tasks quickly. For example, it is not going to be acceptable for warehouse associates to wait 10 or 20 seconds after each case or pallet is received before they can receive the next case or pallet; this kind of performance would cripple productivity at any facility. This type of risk is present on many WMS projects. It is not uncommon to hear of a system that appears to work fine in the lab when one person is testing it, but when 40 people start using it in the actual facility, the system's response time renders it useless. A stress test is used to discover these situations before they happen in the real world.

There are two ways to conduct a stress test. The manual approach is to take 40 or 50 people (whatever the normal load on the system would be) prior to start-up and have them all use the system simultaneously. The second approach is to employ an automated test tool that will *simulate* 40 or 50 people simultaneously banging on the keyboard at the same time. The manual approach isn't difficult to set up, but you cannot run it very often because it interferes with the regular business activity going on in the facility. The second approach is more complicated to set up, but it can be run over and over again.

After several conversations with another customer of this same WMS software vendor, the retailer decided to acquire an automated test tool to do the stress testing. Since the retailer had no one in-house to do this work, the retailer arranged for assistance from a consulting firm specializing in automated test scripting. Two automated test designers thus joined the project in week 94. These designers, working with two programmers/analysts from the retailer's MIS staff, developed the first version of this test. Almost immediately a severe performance problem was identified. For two weeks, the vendor's staff worked two shifts a day trying to solve this problem. Finally, in week 98, the bug was fixed and stress testing continued. It took three more weeks of refining the test and fixing the resulting problems before the analysts finally declared the system ready for duty in week 101.

Performing the Acceptance Test. The last hurdle for the new system was the acceptance test. This test was to be conducted by the users prior to going live. The acceptance test was developed by one of the industrial engineers working very closely with the new manager of the CD facility. This test took a whole week to run through the first time, but after three passes, the users reduced the time to two days. After four passes through the test, the users finally agreed to allow the system to go live in the CD facility.

Lessons Learned during the Testing of the Application. Several good lessons are worth remembering from this stage of the project. *First, don't wait around for the software to be perfect before you begin the acceptance test.* It will take some time for the users to get comfortable using the system and performing the test. If you start the test early, even if you know the system will fail the test, you allow the test team to climb that learning curve. We came very close to delaying the implementation date because the acceptance test team couldn't test fast enough.

Make sure an IS representative or someone who really knows the system watches over the shoulders of the users performing the acceptance test. The project managers failed to do this on the first pass and paid for it. Not only did the users take extra time to perform the test, but they determined that several supposed bugs were really attributable to user error. Worse yet, these problems led some of the users to proclaim that the system was weeks away from being ready to go. *To avoid these headaches, remember to place someone on the acceptance test team who knows how the system works and can recognize a real bug when it occurs.*

Another really important factor to remember is that *the acceptance test team should perform the acceptance test while connected to a live host.* Although few major problems were discovered in the WMS application after the system went live, several issues were discovered with the host interface. This happened because the client's test scripts didn't match actual business conditions exactly. Some of these problems would have been discovered, however, during acceptance testing if the WMS had been connected to a live host.

RESULTS

The installation of the application at the DC as of this writing has not yet occurred. The results for the CD are still less than complete at this point. While employees at the facility are enjoying the cross-docking features in the new software, they still are not using the interleaving capability of the system. Management at the CD have been reluctant to turn on this feature because they don't understand how it works and are afraid that it will hurt productivity rather than help it.

The objective of pushing the maintenance of the software onto the vendor has not happened yet, either. So far, one full-time person and two contract programmers are continuing to modify the CD system on a regular basis. It is unlikely that the vendor will assume that responsibility anytime soon, because the vendor simply does not have enough resources to perform this job adequately.

Both of these outcomes point out the importance of auditing your system results after the software is installed. Because so much energy is expended to get a new WMS running well enough to serve the business, oftentimes the original objectives of the project are forgotten. For this reason it is absolutely essential that someone be designated to audit the results *before* the project is finished. Furthermore, this person should not be a project team member, but should come from some part of the company other than the project. In this way, the fine-tuning that is inevitably necessary to earn the payback is more likely to take place.

How Many Bugs Did They Find?

On this project, nearly 900 bugs were logged from the moment that the first few pieces of inbound code showed up to the point where the project team was disbanded two months after installation at the CD facility. Figure 10.6.8 shows the bug history week by week for this project. This chart, along with backup information summarizing each bug, was known as the *bug list.* The bug list was published every week once the code became stable enough for on-site testing to take place (around week 84).

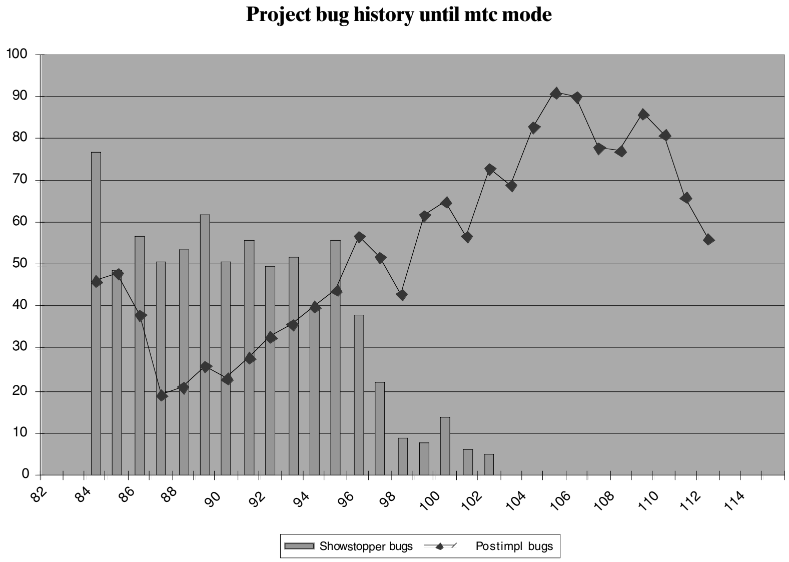


FIGURE 10.6.8 Bug history by week for the CD project.

Note the long period between week 86 and week 96 during which virtually no improvement occurred in the bug count. There were two reasons for this: (1) The bug fixes would cause more problems, or (2) the bugs that were fixed were preventing the test team from testing another piece of the code; once the bugs were fixed and the untouched code tested, bugs would be found in the untested code. This cycle of bug fix–test–bug fix went on until the code suddenly firmed up and the showstoppers decreased noticeably in week 97. Most projects involving lots of customization or programmer time behave like this.

How Much Effort Went into This Project?

Installing a paperless warehouse management system is a sizable project. These efforts take more than just the vendor's time to complete. On many of them, a lot of in-house labor and consulting time are needed. On this project, additional contract programmers had to be brought in to supplement the vendor's development team. This is a bit unusual, but it reflects the fact that oftentimes these projects end up costing a bit more than originally budgeted.

Figure 10.6.9 summarizes the person-hours spent delivering and testing the application installed at the CD facility. A few items need to be explained. First of all, the contractor category includes both consultants and contract programmers/testers whom the retailer retained for some portion of the project. Second, the testing hours reflect not only the unit testing done by the lone tester on the vendor's development team but all of the test preparation and testing performed by the client's test team. Third, the training category contains the three person-hours spent developing the operational procedures as well as the time required for the training team to learn the application, develop the training materials, and then teach the courses. It does not include the time lost by associates when they attended these courses.

Finally, the system support category reflects the time charged to the project by the MIS support staff at the retailer's site. These people are often overlooked, but they were absolutely key to getting the software installed as early as it was. These people performed invaluable tasks such as system administration on the Unix machines, software installation, debugging communication problems, and setting up the training and testing labs. *Do not forget to budget for this category. Furthermore, this retailer discovered that getting someone who is particularly talented in this area can make a huge difference in the pace of the project.*

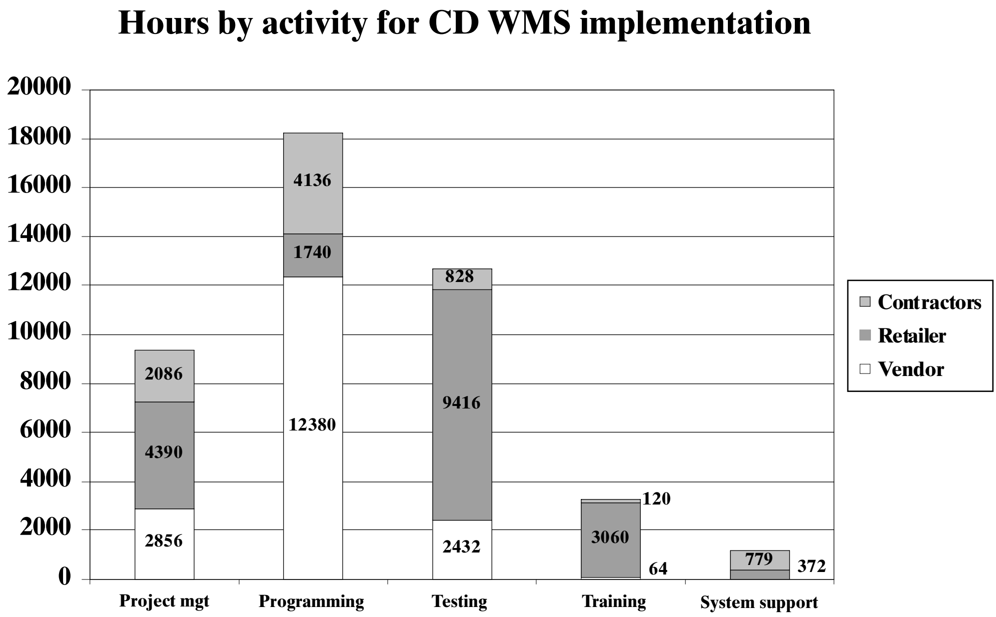


FIGURE 10.6.9 Hours expended by task for the CD installation.

How Much Did This System Really Cost?

When estimating costs for these kinds of projects, one needs to budget for more than just the software. Hardware costs, consulting fees, contractor expenses, travel, special testing tools, and so forth must also be included in the system budget. The following costs for the CD facility are broken out by cost category:

Software (paperless warehouse management software)	$1.5 million
Hardware (computer to run the WMS, network, RF units)	$1.0 million
Contractors and consultants	$1.0 million
Internal staff	$650,000
Travel	$280,000

The total cost of the CD system is estimated to have been close to $4.4 million. A few clarifications of the preceding numbers need to be made: First, very few WMS projects cost this much. This project was unusually expensive due to the large amount of customization involved and the wide variety of problems experienced by the vendor. Second, the aforementioned software costs include the progress payments for the CD installation only. None of the progress payments associated with the DC installation are included. (The DC software was not yet up and running as this was being written.) The software costs also do not include the software testing tools. Third, the hardware costs include 45 radio-frequency terminals. Fourth, the internal staff costs are estimates. To arrive at this figure we used a standard cost of $38 per person-hour to cover salary and benefits. Finally, the travel costs listed include travel not only for the retailer's staff but also for contractors, consultants, and vendor staff related to the project.

SUMMARY

Most paperless WMS projects proceed much more smoothly than the one described here. However, the trials outlined within this case testify to three important success factors that apply to any WMS project. First, be thorough when selecting a vendor. Second, develop contingency plans to keep a project on track. Finally, although most vendors do not suffer from the deficiencies that this one possessed, it is still important to remain vigilant and to act swiftly when vendor performance issues develop.

FURTHER READING

Adams, N., and V. Firth, *Warehouse and Distribution Automation Handbook,* McGraw-Hill, New York, 1996 (book).

BIOGRAPHIES

Steve Mulaik is a director in Logistics Information Systems for The Progress Group, a logistics consulting firm based in Atlanta, Georgia. He has been involved in several warehouse management system selection and implementation projects over his career. Prior to joining The Progress Group, he worked for two Big Six consulting firms and was vice president of

Information Systems at a major convenience store chain. Mulaik has an undergraduate degree in computer science from Georgia Tech and two years of Ph.D. work in operations management, also from Georgia Tech.

Bob Ouellette is the leader in the Logistics Information Systems practice for The Progress Group. He has over 25 years of experience in the planning, design, and implementation of information systems for distribution/warehousing and manufacturing. His prior experience includes the position of vice president of Integration for a logistics software supplier, where he directed efforts in the design and delivery of warehouse and distribution center management systems. Ouellette has held other management positions with General Electric, Black & Decker, Heublein, and SysteCon. He is a frequent speaker at such events as ScanTech, The Logistics Institute at Georgia Tech, Distribution Computer Expo, NCOF, NAWDEC, WERC, ProMat, and Council of Logistics Management (CLM) seminars. Bob earned his undergraduate degree from the State University of New York (SUNY), Brockport.

Source: MAYNARD'S INDUSTRIAL ENGINEERING HANDBOOK

CHAPTER 10.7

CASE STUDY: DEVELOPING ENGINEERED LABOR STANDARDS IN A DISTRIBUTION CENTER

Douglas R. Rabeneck
H. B. Maynard and Company, Inc.
Pittsburgh, Pennsylvania

Terry Kersey
UPS Logistics Group
Atlanta, Georgia

In the diverse business world, there is one function nearly every business has in common: distribution of products. Distribution in many organizations has lagged behind manufacturing, with little focus on labor productivity. For a growing number of organizations, distribution is the principal business. Many distribution operations are implementing sound engineered labor standards, an established management tool that has proven to increase productivity and reduce costs in any industry.

UPS Worldwide Logistics, a third-party provider of logistics services, initiated a comprehensive reengineering project for one of its clients. The goal of this effort was to improve productivity and reduce distribution costs. The development of engineered labor standards to give management a baseline for evaluating performance was one phase in this effort.

This case study details the design and development of labor standards simultaneously for two of Worldwide Logistics' distribution centers.

BACKGROUND

Fragmented best described the supply chain of UPS Worldwide Logistics' client, a large automotive parts manufacturer, before the two firms partnered. In order to serve its 22,000 retail customers, the company's distribution facilities comprised 1.2 million square feet in nine buildings on five sites. The distribution network was not meeting customer expectations for quality, delivery, shipment accuracy, and speed. With half of the critical service elements revolving around accurate on-time delivery, the decision to outsource with UPS Worldwide Logistics (WWL) provided the company with a solution to critical problems.

Improved customer service, increased inventory turns, becoming the low-cost distributor, and expandability to meet future growth strategies were the original objectives for the partnership and keys to developing a solution that allowed for flexibility of output.

In order to bring the customer's distribution function up to world-class standards, WWL began with a network redesign. The new network would consist of two sites instead of five, an East Coast and a West Coast solution. The next step was designing and building two highly automated distribution facilities to meet the client's specific needs.

Several months after bringing the facilities on-line, WWL determined the operation's management teams needed accurate labor planning data to estimate future service costs and to measure performance. External consultants were hired to facilitate the project.

Facility Overview

At the time of the project, both distribution centers were less than a year old. They combined a radio-frequency (RF)-linked warehouse management system (WMS) and a highly automated conveyor sortation system. Customer orders were organized and processed in batches. The two facilities' approximate sizes were 750,000 and 250,000 square feet. The larger employed about 300 and the smaller 75 direct labor associates.

The *receiving* function consisted of both bulk and split-pallet processing. Inbound trailers with split-pallet loads, typically containing many unique products known as *stock-keeping units* (SKUs), were directed to a location adjacent to many aisles of reserve storage pallet racking. Trailers with nonsplit pallets, typically containing one or a few SKUs, were directed to a location adjacent to the bulk reserve storage area. Receiving included trailer unload and checking the inbound products into inventory.

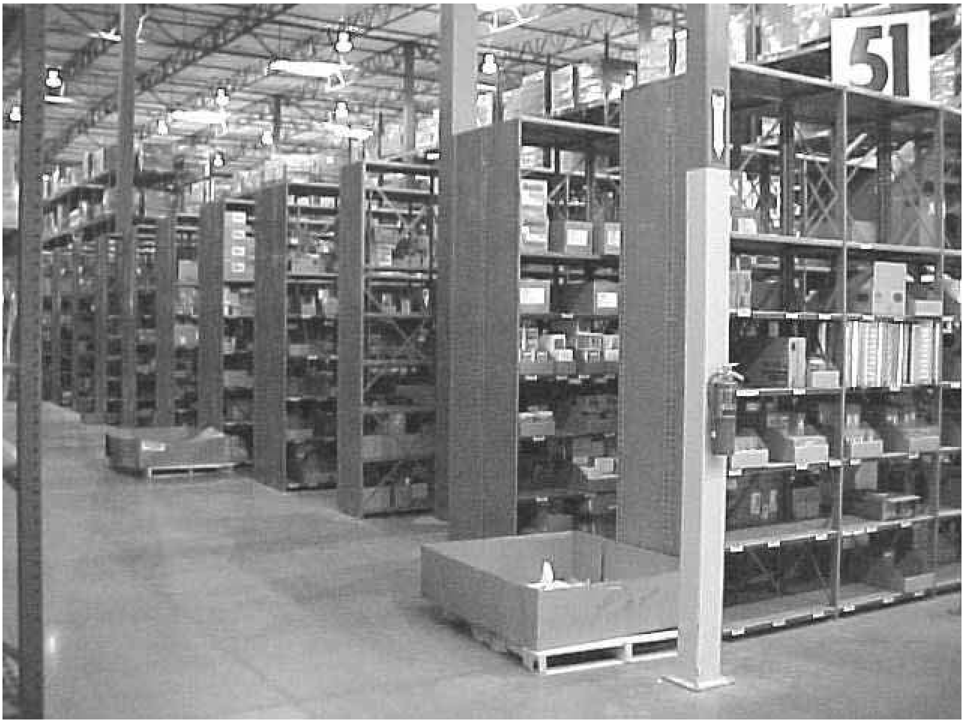


FIGURE 10.7.1 Bin shelving.

Putaway can be simply described as retrieving pallets from the receiving staging area and putting them away into a system-directed reserve storage location.

Replenishment is the function of refilling the product pick locations throughout the distribution center. The WMS system identifies when a location will reach zero inventory and directs associates to a reserve location where the specific SKU is stored.

Product selection is accomplished using several different picking strategies. *Pick to light* is used with both carton flow racks and bin shelving (see Fig. 10.7.1). *Label pick to belt* is done in trilevel pick towers (see Fig. 10.7.2). *Full pallet pick* and *nonconveyable picking* is also used in the facility. Once cartons are selected, they are inducted at several points into the automated conveyor sorting system and sent to either pallet build or to small-parcel shipping.

Pallet build is the final stop of the conveyor system, where the cartons selected to fulfill orders are palletized. Associates utilize 16 lanes to build pallets according to each customer's

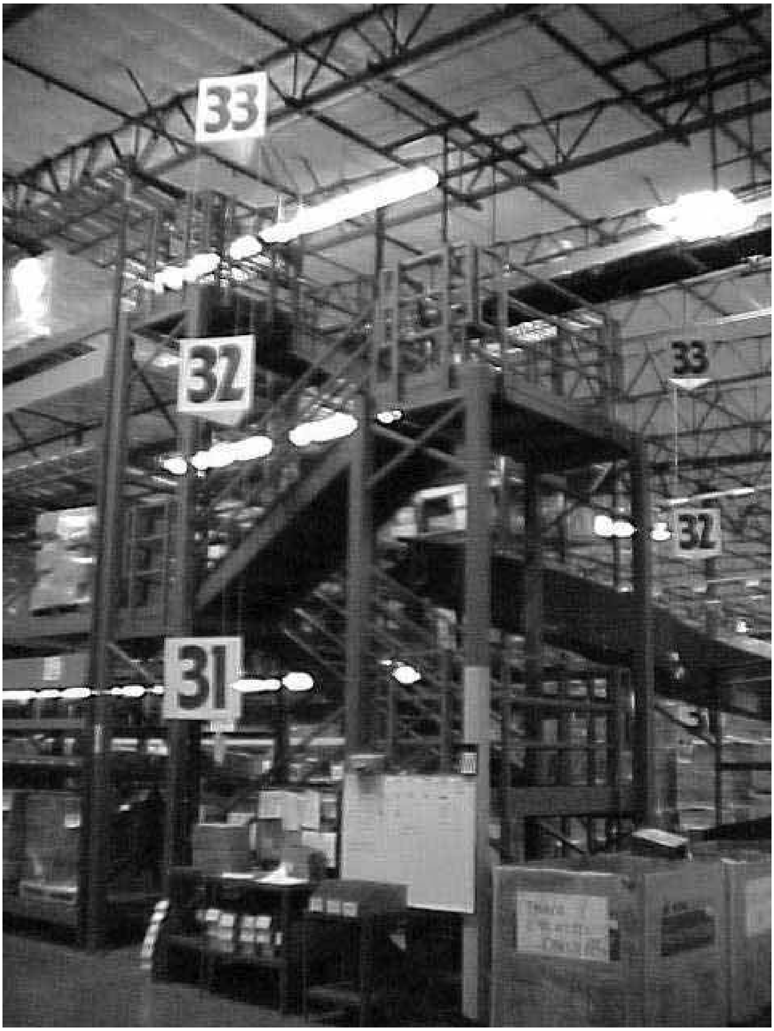


FIGURE 10.7.2 Three-level picking tower.

height and weight specifications (see Fig. 10.7.3). Built pallets are transferred to one of two stations, where they are weighed, covered in stretch wrap, and labeled for shipment.

Completed pallets are staged at one of the outbound dock doors for shipping. The customer orders are either loaded into dedicated trailers or given to less-than-load (LTL) carriers for transportation (see Fig. 10.7.4).

Small-parcel shipping is for orders that are too small to be palletized. All cartons sent to this location are processed, labeled, and staged for pickup by one of several small-parcel carriers (see Fig. 10.7.5).

PROJECT OBJECTIVES

The project began with four primary objectives:

- To develop engineered labor standards for all major direct labor functions (receiving, putaway, picking, shipping, and replenishment)
- To establish a basis for estimating the future service cost for WWL's customer
- To provide sufficiently accurate measures to support a performance management program
- To complete the project in three months

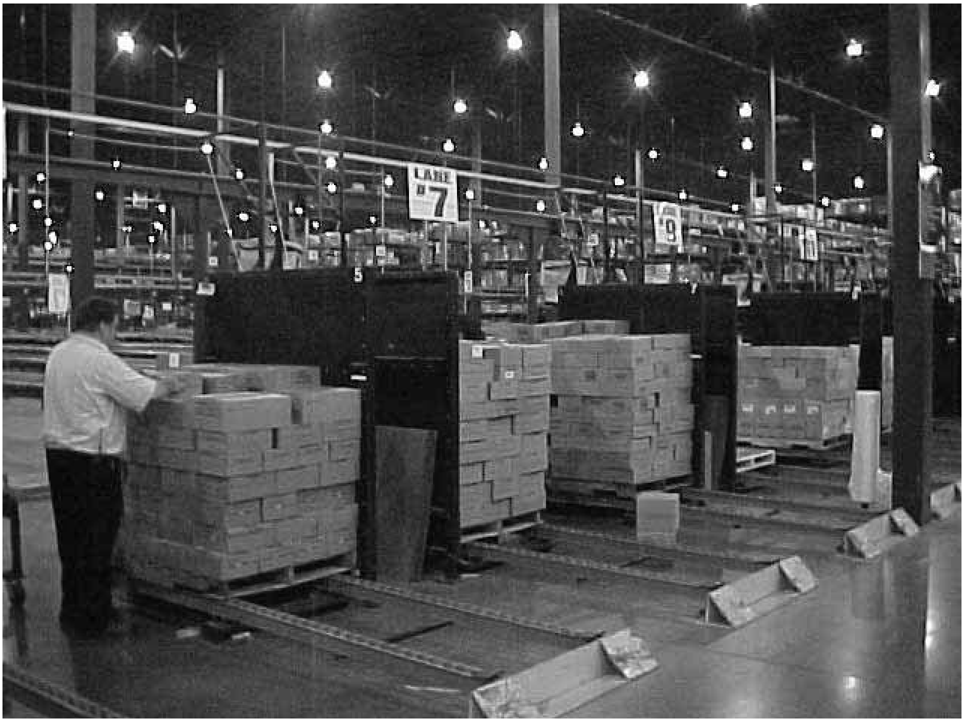


FIGURE 10.7.3 Pallet-building process.

CASE STUDY: DEVELOPING ENGINEERED LABOR STANDARDS IN A DISTRIBUTION CENTER

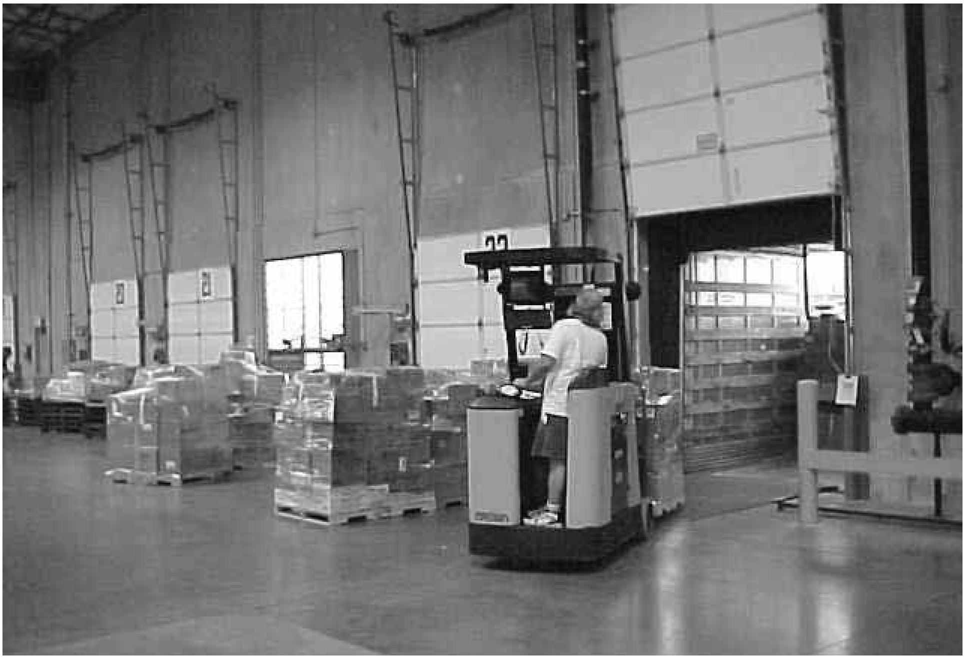


FIGURE 10.7.4 Shipping area.

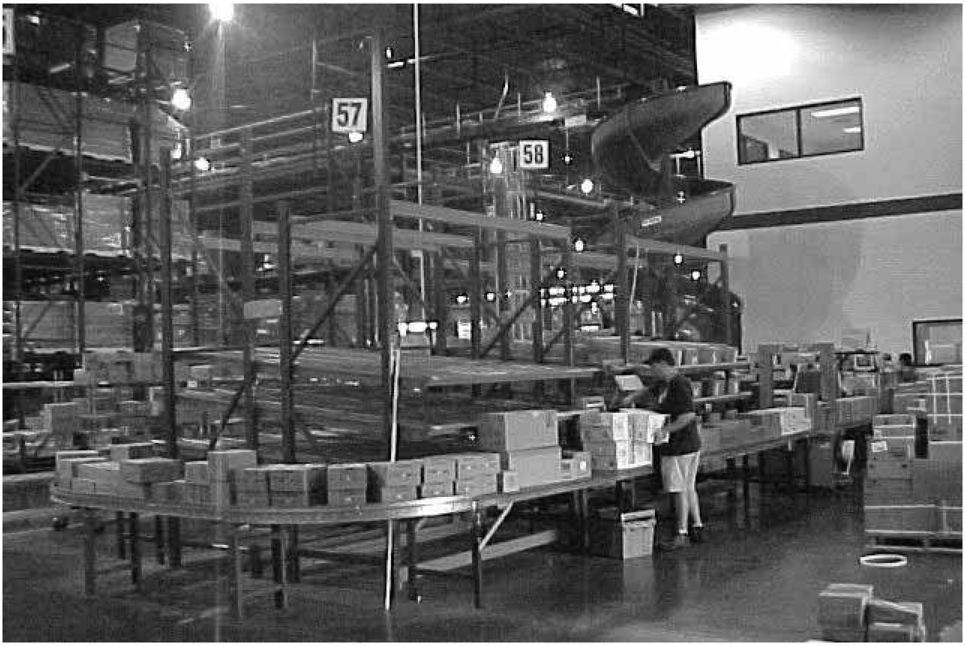


FIGURE 10.7.5 Small-parcel shipping.

WORK MEASUREMENT APPROACH

Due to the variability of tasks in a distribution environment, engineered labor standards for an operation need to be determined either statically or dynamically. Choosing the optimal approach depends primarily on two factors: the desired purpose of the standard and whether the variable characteristics of the operation can be predicted.

Static standards are determined by combining statistical analysis and work measurement to determine the average frequency of occurrence and measured elemental time for each variable in the operation. For example, to develop a static standard for unloading a trailer of palletized freight, one would begin by observing the methods used to complete this task and studying the frequencies of all variables that affect the length of the operation (type of equipment used, equipment travel distance, number of pallets transported per trip, number of pallets contained on the trailer, etc.). After observing many iterations of the operation, the job methods can be engineered and improved. From the frequency study, statistical averages for each variable could be calculated and a representative condition created. The work content of the representative condition is measured to create a standard. If properly developed, static standards are effective because the variations in task duration balance out over time.

Dynamic standards require substantially more information to determine the allowed time for a task. As in static standards, the method must be analyzed and documented, and each variable that affects the length of time required to perform a task must be identified. Those variables that can be predicted prior to the task occurring (location in warehouse, quantity ordered by customer, carton quantity, etc.) become the primary drivers for determining the standard time. In the preceding example of unloading a trailer, a dynamic standard could be calculated if the variables can be predicted (e.g., the trailer contains 34 pallets and they will all be moved to a fixed staging location). Creating dynamic standards also generally requires some type of application software to process the information, follow the defined decision logic, and compute a standard time. In order to identify which approach was the best fit, the project team evaluated the available information and systems to determine its ability to support work measurement. The two primary dividers were time and throughput. The immediate issue was to resolve the degree to which time and throughput information were granular. If the objective was to establish a standard for replenishment, then the time collection system and WMS must be able to provide the information for that specific operation. If these systems could provide only total facility numbers, then this would have to be taken into consideration as the standards were developed.

Because of the limitations in the WMS used by WWL's customer and the inability to predict the work content, the static standards approach was selected. The following steps were taken to develop engineered labor standards:

1. *Defining the units of measure.* The first step in meeting the objectives was to develop a thorough understanding of the processes. The project team observed each process and broke it down into component tasks. A unit of measure was defined for each task, describing the point at which it repeated. A simple example in receiving is the trailer unload process. Unload can be divided into several component tasks (open/close dock door, set trailer hitch, set up or tear down dock leveler, check trailer number, pick up pallets with forklift, transport pallets from trailer to staging, etc.).

In the case of the first five tasks, the unit of measure would be *per trailer,* and all steps in that task occur on a per-trailer basis. The other tasks are likely to repeat on a per-pallet or per-forklift trip basis. Figure 10.7.6 identifies each of the units of measure in the receiving function.

2. *Documenting the methods for each process and task in a given function.* Once the units of measure were defined, the next step was to document the task methods. The project team flowcharted the job methods for each function, beginning with receiving and following the flow of merchandise through the facility. Multiple associates were observed performing the tasks on each shift.

CASE STUDY: DEVELOPING ENGINEERED LABOR STANDARDS IN A DISTRIBUTION CENTER

Function	Process	Receiving element description	Fixed or variable	Unit of measure
Receiving	Setup	Open/close dock door	F	Per trailer
Receiving	Setup	Set trailer hitch	F	Per trailer
Receiving	Setup	Setup/teardown dock leveler	F	Per trailer
Receiving	Setup	Check trailer and hauler number	F	Per trailer
Receiving	Setup	Check packing slip and ATR	F	Per trailer
Receiving	Setup	Call receiving for finished trailer	F	Per trailer
Receiving	Unload	Move pallets from trailer to staging using forklift	V	1 per 2 pallets
Receiving	Unload	Rearrange by model using forklift	V	1 per move
Receiving	Unload	Report in-house damage	F	per incident
Receiving	Unload	Move load from trailer to storage	V	1 per 2 pallets
Receiving	Unload	Obtain empty pallet	V	1 per pallet per model
Receiving	Check-in	Sort onto pallets by model number	V	1 per carton
Receiving	Check-in	Key in model number	V	1 per occurrence
Receiving	Check-in	Calculate quantity on pallet	F	1 per pallet
Receiving	Check-in	Scan model no.	F	1 per pallet
Receiving	Check-in	Find location (reads)	V	1 per pallet
Receiving	Check-in	Apply label	F	1 per pallet
Receiving	Check-in	Scan temp. label	F	1 per pallet
Receiving	Check-in	Draw red line on label	F	1 per model per pallet
Receiving	Check-in	Write location on label, 2 digits	F	1 per model per pallet
Receiving	Check-in	Open and inspect (visual), freq. = 1 per model	V	1 per model
Receiving	Check-in	Call quality assurance	F	1 per occurrence
Receiving	Check-in	Sort split pallets	V	1 per split pallet

FIGURE 10.7.6 Receiving units of measure.

This approach allowed the team to review all of the job methods employed by the associates and determine which were the best. These were analyzed and further engineered for improvement. The result became a standardized "preferred method" for that task and the basis for measuring its work content. A side benefit of this approach was a descriptive list of work instructions that could be used to train new associates in a specific task or process.

3. *Reviewing the task methods and identifying possible exceptions.* The project team met with the management group to discuss the preferred method for each task, and they created a list of possible exceptions. These were reviewed to determine if and how they should be addressed. These exceptions were typically classified in one of the following categories: associates not following the prescribed method; an off-standard condition; an unavoidable delay; or a task variation that needs to be accounted for in the standard. An example of the last case occurred in picking during the pick-to-belt operation. The manual methods used to pick a carton and place it on the belt differed depending on carton weight. Because of this, the standard would have to reflect both methods at the appropriate frequency of occurrence. Figure 10.7.7 shows the standard for the pick-to-belt operation.

4. *Measuring the work content of each task.* After defining and agreeing upon a preferred method for each task, the team was able to begin the work measurement. The project team employed the BasicMOST® technique to establish a normal time for each task. Work measurement software was used to create a concise database of the 150 task elements. This database could be used to set a standard for 95 percent of the direct labor job assignments in the facility.

5. *Measuring the use of material-handling equipment.* Distribution operations typically utilize several types of material-handling equipment. The measurement of this equipment often proves to be challenging. For this project, each facility was divided into zones. As the

Job Description:	PICK TO BELT - TRI LEVEL TOWER		
Function	PICKING	**Unit of Measure**	PER CARTON
PFD Allowance:	15.000	**Units/Cycle:**	1.000
Total Time:	0.00412	**Total Time/Unit:**	0.00412
Frequency Variables::	Cartons per wave = 1000 Cartons per pallet = 50 % light & medium weight cartons = 94% % heavy weight cartons = 6%		
Create Date:	3/29/00	**Effective Date:**	3/29/00

Step:	**ID**	**Title**	**Frequency**	**Hours**
1	635	SIGN OUT LABELS FROM WORK STATION *Elemental frequency = 1 per wave*	1/1000	0.00000
2	672	WALK PICKING PATH *Elemental frequency = 1 per wave*	1/1000	0.00006
3	667	READ PICKING "SCOREBOARD" *Elemental frequency = 6 per wave*	6/1000	0.00000
4	244	READ MODEL NUMBER FROM LABEL *Elemental frequency = 1 per carton*	1.000	0.00060
5	244	READ MODEL NUMBER FROM CARTON *Elemental frequency = 1 per carton*	1.000	0.00060
6	663	APPLY LABEL TO CARTON *Elemental frequency = 1 per carton*	1.000	0.00060
7	664	PICK LIGHT AND MEDIUM CARTONS TO BELT *Elemental frequency = I per carton * % light & medium weight*	0.940	0.00103
8	665	PICK HEAVY CARTONS TO BELT *Elemental frequency = 1 per carton * % heavy weight*	0.060	0.00008
9	639	REMOVE EMPTY PALLET & OPEN NEW ONE *Elemental frequency = 1 per pallet per 50 cartons*	1/50	0.00061

Type	**Elemental Time**	**Allowance Percent**	**Allowance Time**	**Standard Time**
Std (Hours/Cycle)	0.00358	15.00	0.00054	0.00412

Standard Hours/Carton: 0.00412
Cartons/Hour @ 100%: 242.64715

FIGURE 10.7.7 Distribution standard operation report: pick-to-belt standard.

methods for a given task were defined, the origin and destination zones were identified. For example, in the putaway function, forklifts transport pallets from the receiving staging area to one of several thousand reserve locations. By grouping the locations into zones, the team could easily determine that a specific pallet was picked up in receiving in zone 2 and went to a reserve in zone 5. A travel matrix was created to document the distances between the midpoint of each zone. After identifying all of the travel distances, the next step was to compute travel times by vehicle. Team members set up a measured course and randomly selected several pieces of each equipment type. They then timed how long it took each vehicle to travel the distance, including starts and stops. The times and distances were used to complete a linear regression.

Yale Walk-Behind Electric Jack

Average travel speed (in Ft/Sec)

Observed

Travel distance (in feet) *X*	**Travel time (in sec) *Y***
50	19.41
50	19.47
50	18.84
50	17.41
100	32.07
100	31.19
100	31.75
100	31.25
150	46.43
150	45.53
150	46.25
150	45.62

Calculated

Travel time (in sec) *Y* calc
18.51
18.51
18.51
18.51
32.10
32.10
32.10
32.10
45.69
45.69
45.69
45.69

Regression output:

Constant		4.926667
Std err of *Y* est		0.749408
R squared		0.996212
No. of observations		12
Degrees of freedom		10
X coefficient(s)	0.27175	
Std Err of Coef.	0.005299	

$y = mx + b$

From the data the formula is:

$y = 0.272x + 4.93$

Travel Distance Slotting Ranges

$y = 0.272x + 4.93$

(loaded)

Time upper limit (TMU)	**Distance upper limit (feet)**	**Distance range (feet)**	**Time value allowed (TMU)**
170	4	0 - 4	100
420	37	5 - 37	300
770	84	38 - 84	600
1260	149	85 - 149	1000
1960	241	150 - 241	1600
2770	348	242 - 348	2400

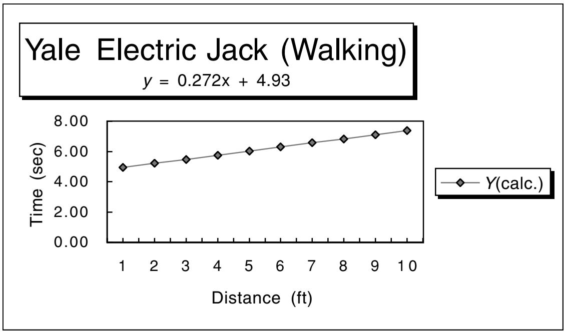


FIGURE 10.7.8 Regression analysis for material-handling equipment.

The result of the regression was a formula for each equipment type dependent on only one variable: travel distance. By following the zone travel approach, the project team knew on any given order there might be more or less travel than allowed in the standard, but that over time the variances would balance out. Figure 10.7.8 is an example of the analysis for one type of equipment.

6. *Setting standards.* A standard for each operation could be calculated by combining all the measured component tasks at their appropriate frequency of occurrence and multiplying

Job Description:	TRAILER UNLOAD		
Function	RECEIVING	**Unit of Measure**	PER PALLET
PFD Allowance:	15.000	**Units/Cycle:**	1.000
Total Time:	0.01372	**Total Time/Unit:**	0.01372
Frequency Variables::	Trailers per day = 15 Pallets per trailer = 50 Pallets per trip = 1.5	Models per trailer = 8 Pallets per shift = 750	
Create Date:	3/29/00	**Effective Date:**	3/29/00

Step:	**ID**	**Title**	**Frequency**	**Hours**
1	620	INSPECT VEHICLE *Elemental frequency = 1 per shift*	1/750	0.00003
2	376	TRAVEL TO DOCK WITH REACH TRUCK *Elemental frequency = 1 per trailer*	1/50	0.00017
3	633	OPEN/CLOSE DOCK DOOR *Elemental frequency = 2 per trailer*	2/50	0.00006
4	616	SET TRAILER HITCH *Elemental frequency = 1 per trailer*	1/50	0.00016
5	434	SETUP OR TEARDOWN DOCK LEVEI *Elemental frequency = 2 per trailer*	2/50	0.00020
6	588	VISUALLY INSPECT TRAILER NUMBER *Elemental frequency = 1 per trailer*	1/50	0.00006
7	617	CHECK PACKING SLIP *Elemental frequency = I per trailer*	1/50	0.00011
8	373	TRAVEL 31-70 FT. WITH SIT DOWN *Elemental frequency = 1.5 per trip (50% 2 pallets, 50% 1 pallet)*	3/2	0.00260
9	607	CHANGE VEHICLE DIRECTION *Elemental frequency = 2 per trip divided by 1.5 pallets/trip*	4/3	0.00185
10	607	CHANGE VEHICLE DIRECTION TO SEGREGATE MODELS *Elemental frequency = 2 per model per trailer*	16/50	0.00044
11	398	RAISE/LOWER FORKS ON REACH TRUCK *Elemental frequency = 1 per model per trailer*	8/50	0.00029
12	606	RAISE & LOWER FORKS TO LIFT FROM FLOOR *Elemental frequency = 2 per trip divided by 1.5 pallets/trip*	4/3	0.00013
13	398	RAISE/LOWER FORKS ON SIT DOWN 56-125 INCHES *Elemental frequency = 2 per trip divided by 1.5 pallets/trip*	4/3	0.00241
14	30	RECORD INBOUND SHIPMENT ON LIST *Elemental frequency = 1 per trailer*	1/50	0.00333
15	249	SCAN DAMAGE *Elemental frequency = 1 per 5 day week*	1/3750	0.00000
16	343	RECORD DAMAGE INFORMATION *Elemental frequency = 1 per 5 day week*	1/3750	0.00000
17	MO	CHANGE BATTERY *Elemental frequency = 1 per shift*	1/750	0.00008

Type	**Elemental Time**	**Allowance Percent**	**Allowance Time**	**Standard Time**
Standard (Hours/Cycle)	0.01193	15.000	0.00179	0.01372

FIGURE 10.7.9 Distribution standard operation report: trailer-unload standard.

the result by an allowance factor (representing personal, rest, and minor unavoidable delay time). Because each element could potentially have a different unit of measure, it was important to correctly calculate its frequency in relationship to the volume driver for the standard. For example, the standard for *trailer unload* was expressed in pallets unloaded per hour. This was the primary volume driver. The majority of elements have the per-pallet unit of measure; others may have a per-trailer or per-shift unit. To create a standard, all units of measure need to be converted into the primary volume driver. Figure 10.7.9 is an example of the standard for trailer unload. The first element, "Inspect vehicle," occurs once per day, but this was converted to per pallet so that the standard can be expressed and calculated by knowing the number of pallets unloaded each day (750 on average).

7. *Validating standards.* Once the standards for each function were completed, the team validated that the sum of the component tasks was an accurate representation of each operation in the facilities. This was accomplished by comparing the methods and conditions documented in the standard to those required to complete the specific operation. The validation highlighted standards where method steps were missed during the initial review so they could be corrected to accurately reflect and represent the processes.

RESULTS AND FUTURE ACTIONS

After the majority of the direct labor assignments were measured via validated engineered labor standards, the facilities management teams wanted to begin reaping the rewards of the effort by putting the information to use. They decided the best way to accomplish this was through the design of a standards application system. To do this, members of WWL's IE modeling group reviewed the standards, grouped them by function, and listed the appropriate volume drivers. They then selected the primary volume drivers that could be forecasted with an acceptable level of accuracy prior to the start of a shift. Figure 10.7.10 shows the primary drivers and their values for the receiving function.

Function	Primary volume drivers	DC 1	DC 2
Receiving	# of inbound trailers/day	24	15
	% of trailers, bulk	82%	80%
	% of trailers, split	18%	20%

FIGURE 10.7.10 Receiving primary volume drivers.

The primary drivers and standards became the basis for a labor planning and scheduling model. By inputting a specific value for each primary driver, the model computes the required labor-hours and resources by DC function for each specific facility. This provided the management teams with a tool for doing both pre- and postoperation analysis. By inputting the projected workload for a shift, as expressed in the primary volume drivers, the model determines the daily staffing requirements by function. By comparing the actual hours and volumes to the planned labor-hours, the model calculates the operation's effectiveness to standard.

Throughout the duration of the standards development effort, the project team generated numerous process and method improvement suggestions. At the conclusion of the project, the management teams at both facilities prepared plans to evaluate and begin implementing these improvement ideas. Also, the local and corporate IE groups began investigating time- and labor-reporting software with the goal of implementing, in the near future, a system to track individual associate performance.

CONCLUSION

It is very difficult to be successful without accurate information to help one make informed decisions. For over a hundred years, labor standards have proven to be an effective tool for driving significant improvement across all industries. Distribution operations, typically very labor-intensive, is one industry that is beginning to recognize the importance and value of engineered labor standards.

BIOGRAPHIES

Douglas Rabeneck is a senior account manager at H. B. Maynard and Company, Inc. He helps companies design solutions to improve productivity and manages the implementation of these solutions. As an industrial engineering consultant for Maynard, he has facilitated projects with companies in the manufacturing, distribution, banking, utility, and government sectors.

Rabeneck graduated from the University of Pittsburgh with a B.S. degree in industrial engineering. Prior to joining Maynard, he spent eight years working for an international package distribution company in a variety of industrial engineering and operations management roles.

Terry Kersey is the director of Corporate Industrial Engineering for UPS Worldwide Logistics. His primary responsibilities are work measurement, reengineering, and development of internal modeling software for WWL. He has 21 years of industrial engineering experience with United Parcel Services in ground, air, and logistics operations.

Kersey graduated from the University of Florida with a B.S. degree in business administration. While on active duty with the Air Force, he obtained his M.B.A. from Louisiana Tech.

Source: MAYNARD'S INDUSTRIAL ENGINEERING HANDBOOK

S • E • C • T • I • O • N • 11

STATISTICS AND OPERATIONS RESEARCH AND OPTIMIZATION

CHAPTER 11.1

APPLIED STATISTICS FOR THE INDUSTRIAL ENGINEER

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Statistical methods enable the industrial engineer to make better decisions in the context of the variability inherent to engineering processes. This chapter introduces fundamental ideas of statistical thinking: quantifying and explaining variability in sampled data and appropriately accommodating this variability when drawing conclusions. The key statistical concepts presented are obtaining and graphically displaying sampled process data, selecting an appropriate probability model for the data, and using the model to draw conclusions of interest. The chapter then discusses and illustrates three broad classes of statistical models particularly useful to industrial engineers, concluding with an overview of additional relevant techniques.

INTRODUCTION

Often, engineers believe that they can precisely predict (or control) a process if they know (or can control) the variables entering that process. This belief produces the familiar mathematical model $y = f(\mathbf{x})$, where $f(\cdot)$ is a known function relating a vector $\mathbf{x}$ of input variables to y, a process response of interest. Real-world processes, however, vary for unknown or uncontrollable reasons. This extra variation is difficult to account for in the short term, but usually exhibits enough regularity in the long run to be estimated with some confidence. Statistical methods are based on models that exploit this regularity, often taking the form $y = f(\mathbf{x}) + \varepsilon$, where ε refers to the variation not explained by the input variables.

By carefully formulating a statistical model and using appropriate statistical techniques, practicing engineers can obtain not only estimates of process outcomes, but also measures of the uncertainty of these estimates. This information will enhance decision making by clarifying both the chance of making an error and the consequences of any error.

This chapter is an introduction to important statistical concepts for industrial engineers. The key to statistical thinking is acknowledging variability and incorporating the uncertainty that it creates in our inferences. This chapter focuses on methods the engineer can use to quantify and explain variability in real-world processes. Important concepts are introduced for obtaining data, selecting a model for the data, drawing conclusions from the fitted model, and checking the model's appropriateness. Next, three types of models that are particularly useful for industrial engineers are presented; these are certain univariate reliability models, control charts, and linear regression. The chapter concludes with an overview of additional useful techniques, including a number of more modern methods. It is impossible to cover all relevant topics, of course, but references are provided for more detail, and this chapter's material is sufficient background to permit effective consultation with a professional statistician.

DATA

Observational and Experimental Data

Statistical inference is the process of using data obtained from a subset of some population of interest to learn about important features of the population. For example, we may wish to characterize the performance of the 150 workstations (the population) in use by a consulting company, but time or cost constraints may permit evaluation of the performance of only a subset of 10 workstations. Naturally, the quality of the data determines the quality of the conclusions ("garbage in, garbage out"), so in this context it is important to understand how the sample of 10 workstations was obtained. In particular, it is highly desirable that the sample be representative of the population, which is usually the case when the sampled subset is selected *at random,* meaning that all workstations have the same chance of being selected for the sample. In contrast, if the 10 sampled machines were those most recently purchased, the performance (speed, say) of this subset is likely to be substantially better than that of the population as a whole. Thus, one must be careful about using data that happen to be on hand and for which the sampling mechanism is often not known when making inferences about the larger population. Such data are called *observational,* and cautions about the biases they may introduce abound. (See, for example, Ref. 1, p. 57; Ref. 2, p. 230; Ref. 3, p. 493.)

Whenever possible, then, it is preferable to collect data specifically for the question of interest in order to obtain a representative sample. An important case of planned data collection to address a research question is *designed experimentation.* Here interest focuses on how explanatory variables $\mathbf{x}$ affect the process outcome y, and the ideal data are those obtained by setting the input variables $\mathbf{x}$ according to a prespecified scheme and recording the corresponding values of y. A simple but powerful example of experimental design is discussed later in this chapter under the heading Two-Level Factorial Designs.

Types of Data

Data may be categorical (qualitative) or quantitative. *Categorical* data arise from any variable measured strictly by classification into distinct and well-defined sets. A *quantitative* variable yields a numerical value. A *discrete quantitative variable* (often termed simply a *discrete variable*) is one for which the possible values come from a discrete set, often whole numbers. A *continuous quantitative variable* (*continuous variable*) is one that takes values in an interval of the real numbers. This chapter addresses methods for some of the more commonly occurring quantitative data; methods for analyzing categorical data are thoroughly addressed in Ref. 4.

Data Displays and Summaries

The presentation of categorical data is typically straightforward. A table listing the categories and the number or percentage of observations falling into each category is usually sufficient. To increase the readability of such tables, categories that appear infrequently are often pooled into an "other" category. Graphical displays of these tables can be made using bar charts or pie charts.

Quantitative data are summarized graphically and numerically, with the goals of describing the data according to its *location* (central values), *variability* (spread of values about the center), *shape* (distribution of values about the center, such as symmetric or skew), and the presence of any highly unusual values (*outliers*). As an example, Fig. 11.1.1 shows a *histogram* [1, p. 14; 2, p. 9] of the $n = 40$ fill volumes from an orange juice canning process given in Table 11.1.1. Examination of this chart reveals that a typical fill amount is about 358 ml; fill amounts commonly range from 356 to 361 ml, with values farther from 358 somewhat more common in the right tail (a shape referred to as *right skewness*); and there is one unusually low-fill amount of about 353 ml.

TABLE 11.1.1 Juice Fill Amounts (ml)

356.8	360.1	358.2	357.1	358.6	357.9	357.7	358.3
357.5	357.5	358.2	357.8	356.2	358.0	356.7	359.8
356.4	360.6	359.2	357.1	358.6	359.2	358.5	357.9
359.4	359.2	358.5	358.2	358.6	358.0	355.4	356.8
357.1	356.7	362.9	357.7	357.1	357.9	361.6	353.0

Numerical summaries can aid the interpretation of these statements. Table 11.1.2 gives expressions for the usual summaries computed for observations of a continuous variable. For the fill amounts displayed in Fig. 11.1.1, we find that the average value is $\overline{y} = 358.1$ ml; the median is $Q_y(0.5) = 358.0$ ml; the sample standard deviation is $s_y = 1.7$ ml; and the lower and upper quartiles are $Q_y(0.25) = 357.1$ ml and $Q_y(0.75) = 358.6$ ml.

Graphical displays are essential to good data analysis. Numerical summaries alone can be misleading, as important features of the data distribution, such as outliers or multimodality, can be overlooked. The need for graphical displays is even greater when studying the very large data sets routinely collected by modern manufacturing processes; a handful of numeri-

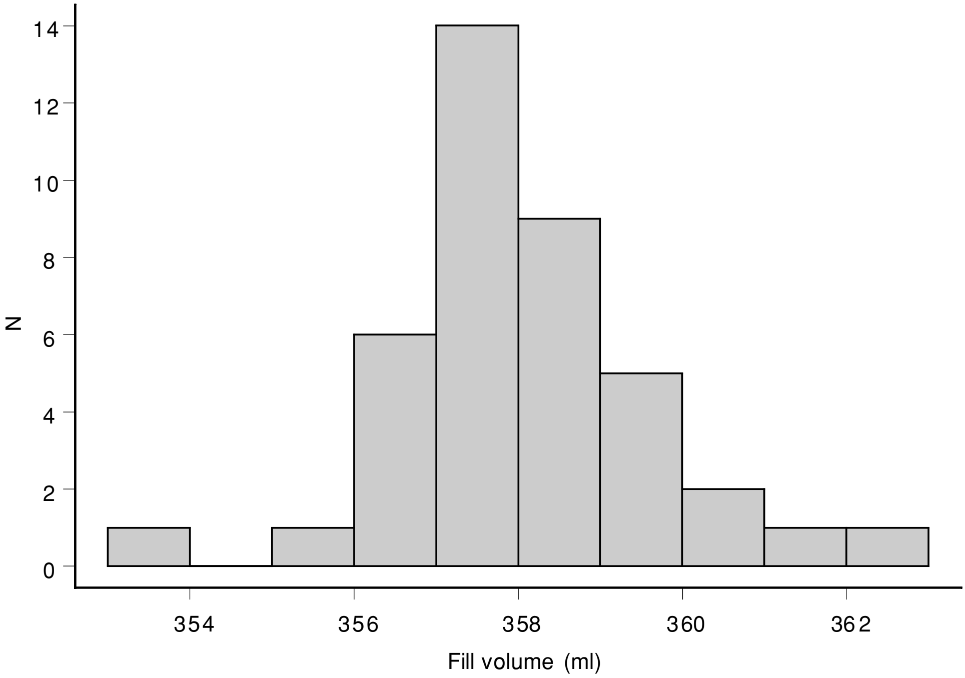

FIGURE 11.1.1 Histogram of the fill amounts given in Table 11.1.1.

TABLE 11.1.2 Numerical Summaries for a Sample

Sample data	$y_1, y_2, \ldots, y_n$
Sorted data	$y_{(1)} \le y_{(2)} \le \ldots \le y_{(n)}$
Sample average	$\bar{y} = \frac{1}{n} \sum_{i=1}^{n} y_i$
Sample standard deviation	$s_y = \left[\frac{1}{(n-1)} \sum_{i=1}^{n} (y_i - \bar{y})^2 \right]^{1/2}$
Sample quantiles* $(0 < p < 1)$	$Q_y(p) = y_{(pn+0.5)}$

* When $pn + 0.5$ is noninteger, $Q_y(p)$ is the appropriately weighted average of the observations with ranks just before and just after $pn + 0.5$.

cal summaries is unlikely to adequately describe megabytes of data. Additional important data displays are a plot of the data-versus-observation number (a time sequence plot) and, for multiple variables recorded on each item, scatter plots. More on these and other graphics can be found in Ref. 1, Chp. 1, and Ref. 5.

PROBABILITY MODELS

The aforementioned graphical and numerical methods describe sample data obtained from a population. Most often, however, the population, not the sample data, is of primary interest. Rather than merely describing the 40 fill volumes in Table 11.1.1, for instance, it is desirable to use these data to draw conclusions about the population of all fill volumes produced by this process. Such *statistical inferences* are based on a model for the process that generated the sample data. This model is necessarily *stochastic,* or *probabilistic,* because the process outcome is uncertain until observed.

A probability model is specified by representing the process outcome as a *random variable* [2, p. 81] that takes values in the population according to a *probability distribution.* Letting Y denote the random variable, the probability distribution is given by the *cumulative distribution function* (cdf) for Y, $F_Y(y) = P(Y \le y), y \in \Re$, where $P(E)$ is the probability of the event E. Additionally, if Y is a discrete random variable (meaning its observation yields discrete data), its probability distribution may be specified by a *probability mass function* (pmf), $p_Y(y_i) = P(Y = y_i)$, which gives the probability that Y assumes each of its possible discrete values. If Y is a continuous random variable, its distribution may be specified by either the cdf or the *probability density function* (pdf). The pdf is a positive function, $f_Y(y)$, that gives probabilities when integrated: $P(a \le Y \le b) = \int_a^b f_Y(u)du$ for all intervals $[a, b]$. Thus the pdf is the derivative of the cdf and integrates to one on the real line.

To fix these ideas, consider again the evaluation of the 150 workstations at the consulting company. Suppose that 50 of these workstations were purchased within the last year and, as before, constraints permit the evaluation of only a random subset of 10 of the 150 machines. The number of workstations in the sample that are new is a discrete random variable that may take values 0, 1, . . . , 10. Intuition suggests that a value of 10 is quite unlikely and that there will be three or four (10/3 = 3.3) new workstations in the sample, typically. Indeed, knowing that there are 50 new workstations among the 150 completely specifies the probability distribution for the number of new workstations in the sample (this is the hypergeometric distribution described in the next section). The fill volume in the juice canning process, on the other hand, is a continuous random variable because any value between zero and a can's capacity is possible. Values of around 358 ml are more likely, however, so we would expect the pdf to be roughly mound-shaped, with most of its mass within 5 ml of 358.

In statistics, the population probability distribution is not known, but it is usually possible to specify a family of distributions that is likely to include a good approximation to the true population distribution. Each family is indexed by *parameters* that control features of the distributions—for example, the location and spread. Statistical inference proceeds by selecting from within the family the model that is most likely to have generated the data observed. Thus, once the family is selected, the observed data are used to determine the appropriate values of the family's parameters.

A number of families that are useful in engineering are listed subsequently. The *mean* and *variance* are important summaries of a probability distribution. The mean or *expected value* of the random variable Y is the center of mass of its distribution $\mathrm{E}(Y) = \int_{-\infty}^{\infty} u f_Y(u)\,du$, while the variance is the expected squared deviation about the mean, $\mathrm{Var}(Y) = \int_{-\infty}^{\infty} (u - \mathrm{E}(Y))^2 f_Y(u)\,du$. (Replace the integrals and pdf's by sums and pmf's in the discrete case.) The *standard deviation* is the square root of the variance. Expressions for these quantities are also given for each family, as they are useful for comparing the probability model to the data distribution.

Selected Discrete Probability Models

Hypergeometric. Suppose a lot contains N items, of which m are nonconforming. If a random sample of size n is drawn from the lot without replacement, and Y is the number of nonconforming items in the sample, then Y has a hypergeometric distribution.

$$\text{pmf:} \qquad P(Y = y) = \frac{\binom{m}{y}\binom{N-m}{n-y}}{\binom{N}{y}}, \qquad \max(0, n - N + m) \le y \le \min(n, m)$$

$$\mathrm{E}(Y) = nm/N \qquad \mathrm{Var}(Y) = nm(N-m)(N-n)/[N^2(N-1)]$$

When the population size N is large relative to the sample size n, the hypergeometric pmf is well approximated by the binomial pmf.

Binomial. Consider a manufacturing process that produces a stream of product, each unit of which is either conforming or nonconforming. Suppose the probability that a unit is nonconforming is a constant p, $0 \le p \le 1$, and that the units are *independent*, meaning that the quality of a unit is unrelated to the quality of other units. Then the number of nonconforming units in a random sample of size n from the process has a binomial distribution with parameters n and p. Denoting this random variable by Y, its pmf, mean and variance are as follows:

$$\text{pmf:} \qquad P(Y = y) = \binom{n}{y} p^y (1-p)^{(n-y)}, \qquad y = 0, 1, \ldots, n$$

$$\mathrm{E}(Y) = np \qquad \mathrm{Var}(Y) = np(1-p)$$

Negative Binomial. In the same situation as described for the binomial distribution, let Y be the total number of units produced until r conforming units have been made. Then Y follows a negative binomial distribution with parameters p and r.

$$\text{pmf:} \qquad P(Y = y) = \binom{y-1}{r-1} p^r (1-p)^{(y-r)}, \qquad y = r, r+1, \ldots$$

$$\mathrm{E}(Y) = r/p \qquad \mathrm{Var}(Y) = r(1-p)/p^2$$

Poisson. The Poisson distribution is useful for modeling the number of nonconformities that occur on a per-unit (or per-unit-area, per-unit-volume, per-unit-time, etc.) basis. If the nonconformities have constant average density, say λ, per unit, then the random variable Y given by the number of nonconformities per unit has a distribution well approximated by the Poisson with parameter λ.

$$\text{pmf:}\qquad P(Y = y) = e^{-\lambda}\lambda^y/y!, \qquad y = 0, 1, \ldots$$

$$\mathrm{E}(Y) = \lambda \qquad \mathrm{Var}(Y) = \lambda$$

Selected Continuous Probability Models

Normal. The normal, or Gaussian, distribution is extremely useful because many continuous measurements are approximately normally distributed. If Y is normally distributed with parameters μ and σ^2, written $Y \sim \mathrm{N}(\mu,\sigma^2)$, then its pdf, mean, and variance are

$$\text{pdf:}\qquad f_Y(y) = \frac{1}{\sigma\sqrt{2\pi}} \exp\left[-\frac{1}{2}\left(\frac{y-\mu}{\sigma}\right)^2\right], \qquad -\infty < y < \infty$$

$$\mathrm{E}(Y) = \mu \qquad \mathrm{Var}(Y) = \sigma^2$$

The normal pdf is a symmetric, unimodal, bell-shaped curve, centered at the parameter μ, with spread controlled by σ. A useful property is that if $Y \sim \mathrm{N}(\mu,\sigma^2)$ and Z is the standardization of Y, $Z = (Y - \mu)/\sigma$, then $Z \sim \mathrm{N}(0, 1)$. Thus, although the cdf of the normal distribution is not in closed form, the cdf of the N(0, 1) distribution (available in Table 11.1.3) can be used to obtain cdf values for any other normal distribution: $P(Y \le y) = P[Z \le (y - \mu)/\sigma]$ for Y and Z as before. It is not mere coincidence that the normal distribution is so widely applicable. The *central limit theorem* [2] shows that most sums of random variables are approximately normally distributed. Thus, because measurement errors tend to be sums of many small errors, continuous measurements tend to be approximately Gaussian.

Weibull. The Weibull is a flexible family of distributions for modeling lifetimes (the life of a part, a human, a waiting time, etc.). If the random variable Y has a Weibull distribution with parameters $\beta > 0$ and $\theta > 0$, its pdf, mean, and variance are as follows:

$$\text{pdf:}\qquad f_Y(y) = \beta\theta^{-\beta}y^{\beta-1}e^{-(y/\theta)^\beta}, \qquad y \ge 0$$

$$\mathrm{E}(Y) = \theta\,\Gamma(1 + 1/\beta) \qquad \mathrm{Var}(Y) = \theta^2[\Gamma(1 + 2/\beta) - \Gamma(1 + 1/\beta)]$$

where $\Gamma(x) = \int_0^\infty u^{x-1}e^{-u}du$, $x > 0$, is the gamma function. When $\beta = 1$, Y is said to have the *exponential* distribution with mean θ. The exponential distribution has the interesting "memoryless" property that an item that has lasted t time units has no greater chance of failing in the next instant than a brand-new item. The Weibull distribution, however, permits both smaller ($\beta < 1$) and greater ($\beta > 1$) chance of failure after surviving t units.

Random Sampling

Much of this chapter concerns inference based on a random sample. This means that there are random variables $Y_1, Y_2, \ldots, Y_n$, each drawn from the same population distribution, none of which influences the value of any other (they are *mutually independent*). It is useful to know the mean and variance of the sample mean, $\overline{Y} = \frac{1}{n}\sum_{i=1}^{n} Y_i$, in terms of the population mean μ and variance σ^2: $\mathrm{E}(\overline{Y}) = \mu$ and $\mathrm{Var}(\overline{Y}) = \sigma^2/n$. The probability distribution for $\overline{Y}$ is hard to compute, in general, but there is an important special case where it is easy—if the $\{Y_i\}$ are drawn from a normal distribution, then $\overline{Y}$ is also normally distributed.

Selecting a Model

Inference about the population depends on the model selected, so it is important to make this choice carefully. Experience with both statistical modeling and the process generating

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TABLE 11.1.3 The Normal Probability Distribution Function, $F(z)$

z	.00	.01	.02	.03	.04	.05	.06	.07	.08	.09
0.0	.5000	.5040	.5080	.5120	.5160	.5199	.5239	.5279	.5319	.5359
0.1	.5398	.5438	.5478	.5517	.5557	.5596	.5636	.5675	.5714	.5753
0.2	.5793	.5832	.5871	.5910	.5948	.5987	.6026	.6064	.6103	.6141
0.3	.6179	.6217	.6255	.6293	.6331	.6368	.6406	.6443	.6480	.6517
0.4	.6554	.6591	.6628	.6664	.6700	.6736	.6772	.6808	.6844	.6879
0.5	.6915	.6950	.6985	.7019	.7054	.7088	.7123	.7157	.7190	.7224
0.6	.7257	.7291	.7324	.7357	.7389	.7422	.7454	.7486	.7517	.7549
0.7	.7580	.7611	.7642	.7673	.7704	.7734	.7764	.7794	.7823	.7852
0.8	.7881	.7910	.7939	.7967	.7995	.8023	.8051	.8078	.8106	.8133
0.9	.8159	.8186	.8212	.8238	.8264	.8289	.8315	.8340	.8365	.8389
1.0	.8413	.8438	.8461	.8485	.8508	.8531	.8554	.8577	.8599	.8621
1.1	.8643	.8665	.8686	.8708	.8729	.8749	.8770	.8790	.8810	.8830
1.2	.8849	.8869	.8888	.8907	.8925	.8944	.8962	.8980	.8997	.9015
1.3	.9032	.9049	.9066	.9082	.9099	.9115	.9131	.9147	.9162	.9177
1.4	.9192	.9207	.9222	.9236	.9251	.9265	.9279	.9292	.9306	.9319
1.5	.9332	.9345	.9357	.9370	.9382	.9394	.9406	.9418	.9429	.9441
1.6	.9452	.9463	.9474	.9484	.9495	.9505	.9515	.9525	.9535	.9545
1.7	.9554	.9564	.9573	.9582	.9591	.9599	.9608	.9616	.9625	.9633
1.8	.9641	.9649	.9656	.9664	.9671	.9678	.9686	.9693	.9699	.9706
1.9	.9713	.9719	.9726	.9732	.9738	.9744	.9750	.9756	.9761	.9767
2.0	.9772	.9778	.9783	.9788	.9793	.9798	.9803	.9808	.9812	.9817
2.1	.9821	.9826	.9830	.9834	.9838	.9842	.9846	.9850	.9854	.9857
2.2	.9861	.9864	.9868	.9871	.9875	.9878	.9881	.9884	.9887	.9890
2.3	.9893	.9896	.9898	.9901	.9904	.9906	.9909	.9911	.9913	.9916
2.4	.9918	.9920	.9922	.9925	.9927	.9929	.9931	.9932	.9934	.9936
2.5	.9938	.9940	.9941	.9943	.9945	.9946	.9948	.9949	.9951	.9952
2.6	.9953	.9955	.9956	.9957	.9959	.9960	.9961	.9962	.9963	.9964
2.7	.9965	.9966	.9967	.9968	.9969	.9970	.9971	.9972	.9973	.9974
2.8	.9974	.9975	.9976	.9977	.9977	.9978	.9979	.9979	.9980	.9981
2.9	.9981	.9982	.9982	.9983	.9984	.9984	.9985	.9985	.9986	.9986
3.0	.9987	.9987	.9987	.9988	.9988	.9989	.9989	.9989	.9990	.9990
3.1	.9990	.9991	.9991	.9991	.9992	.9992	.9992	.9992	.9993	.9993
3.2	.9993	.9993	.9994	.9994	.9994	.9994	.9994	.9995	.9995	.9995
3.3	.9995	.9995	.9995	.9996	.9996	.9996	.9996	.9996	.9996	.9997
3.4	.9997	.9997	.9997	.9997	.9997	.9997	.9997	.9997	.9997	.9998
3.5	.9998	.9998	.9998	.9998	.9998	.9998	.9998	.9998	.9998	.9998

Tail probability, α	0.100	0.050	0.025	0.010	0.005
Upper percentage point, z_α	1.282	1.645	1.960	2.326	2.576

$$F(z) = \int_{-\infty}^{z} \frac{e^{-t^2/2}}{\sqrt{2\pi}}\, dt$$

$$F(-z) = 1 - F(z)$$

the data aid good model selection. One helpful tip is that the range of values possible under the model should match closely the data values that could potentially be observed. Thus, the number of nonconforming items in a batch of 20 is better modeled by a binomial than a Poisson distribution, and the log of cost is often better modeled by a normal distribution than cost itself. The applications discussed in the next section should serve as guides in many situations.

ESTIMATION AND INFERENCE

Two of the most useful probability models in engineering are the normal and binomial distributions. For each of these models, this section describes inferential procedures for two representative scenarios an industrial engineer might face: comparing a process to specifications and comparing two processes. The concepts that are illustrated carry over to many additional practical problems in engineering.

Example A: The tensile strength of blocks formed from a rubber compound is a continuous random variable with distribution approximated well by the normal with parameters μ and σ^2.

Scenario 1. Does the current process satisfy the specification that the mean tensile strength be 210 kg/cm^2?

Scenario 2. Manufacturers A and B produce similar compounds. Is the mean tensile strength greater for manufacturer B's process?

Example B: The number of nonconforming piston rings in a random sample of size n from production is modeled by a binomial distribution with parameters n and p.

Scenario 1. A customer requires that the long-run fraction nonconforming produced by the process be at most 0.01. Is this process satisfactory?

Scenario 2. A modification is meant to reduce the process fraction nonconforming. Has the process improved?

Both scenarios pose questions about population parameters—μ and p for scenario 1 and, additionally, these values for a second process in scenario 2. Statistical evaluation uses random samples from the processes to estimate the unknown population parameters and addresses the questions *in light of the uncertainty in these estimates.*

Normal Sampling: Example A

Let Y be a random variable representing the tensile strength of a randomly selected block formed from the rubber compound. Thus $Y \sim \mathrm{N}(\mu, \sigma^2)$, where the parameters μ and σ^2 may be unknown. To learn about the unknown parameters, a random sample $Y_1, Y_2, \ldots, Y_n$ is drawn from the population so that $Y_i \sim N(\mu, \sigma^2)$, $i = 1, 2, \ldots, n$. Because the population is normal, in addition to the properties $\mathrm{E}(\overline{Y}) = \mu$ and $\mathrm{Var}(\overline{Y}) = \sigma^2/n$, $\overline{Y}$ follows a normal distribution and $(\overline{Y} - \mu)/(\sigma/\sqrt{n}) \sim \mathrm{N}(0, 1)$.

Scenario 1 (σ known): Suppose that the population mean tensile strength μ is unknown, but that the standard deviation is $\sigma = 7$ kg/cm^2. The specification is that $\mu = 210$ kg/cm^2. Suppose further that time and cost considerations permit the evaluation of $n = 25$ blocks drawn randomly from the process and that these have a sample average tensile strength of $\overline{y} = 207$ kg/cm^2. Because $E(\overline{Y}) = \mu$, the observed value $\overline{y}$ is a good *point estimator* for μ. Indeed, these data seem to support a population mean of 210 kg/cm^2, but might another sample from the process yield an average tensile strength further from 210, say only 200 or perhaps as much as 225 kg/cm^2? It is this sampling uncertainty that must be incorporated in the conclusion.

Confidence Intervals. One way to accommodate the uncertainty is to provide a range of plausible values for μ rather than merely the point estimate. An *interval estimate,* or *confidence interval,* for a population parameter is an interval computed using a procedure that has a particular desirable property: of all intervals produced by this procedure, each beginning with a new sample from the population, a specified proportion will contain the true, but unknown, value of the population parameter. The proportion of such intervals that cover the true population parameter is called the *confidence level* of the interval.

Consider estimation of a general population parameter θ using the point estimator $\hat{\theta}$. The confidence intervals discussed in this chapter take one of three forms. Using the confidence level $1 - \alpha$, these are as follows:

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- The two-sided interval $[\hat{\theta} - c_{\alpha/2}s_{\hat{\theta}}, \hat{\theta} + c_{\alpha/2}s_{\hat{\theta}}]$
- The one-sided lower interval $[\hat{\theta} - c_{\alpha}s_{\hat{\theta}}, \infty)$ (11.1.1)
- The one-sided upper interval $(-\infty, \hat{\theta} + c_{\alpha}s_{\hat{\theta}}]$

where $s_{\hat{\theta}}$ is an estimate of the standard deviation of $\hat{\theta}$ and c_α is a *critical value* depending on the form of the sampling distribution of $\hat{\theta}$. The one-sided intervals are appropriate when a number that is likely to bound θ above or below is desired; otherwise, the two-sided interval is used.

When $Y_1, Y_2, \ldots, Y_n$ are a random sample from a normal distribution with unknown mean μ and known variance σ^2, confidence intervals for μ are formed using Eq. (1) with $\hat{\theta} = \bar{y}$, the observed average of the sample, $s_{\hat{\theta}} = \sigma/\sqrt{n}$, and $c_\alpha = z_\alpha$, the critical value satisfying $P(Z > z_\alpha) = \alpha$ for $Z \sim N(0, 1)$. Values of z_α are available from Table 11.1.3 or any statistical software package. Common confidence levels are 90 and 95 percent, for which the required values are $z_{.10} = 1.282$, $z_{.05} = 1.645$, and $z_{.025} = 1.960$.

Example A (continued): A 90 percent two-sided confidence interval for the mean tensile strength of the rubber blocks is $207 \pm 1.645(7/\sqrt{25}) = [204.7, 209.3]\text{kg/cm}^2$. Because this interval has 90 percent confidence of covering the process mean tensile strength μ, yet does not cover 210 kg/cm^2, the data support, with 90 percent confidence, the assertion that the specification is not met. A higher level of confidence that the interval covers μ requires a wider interval: a 95 percent confidence interval for μ based on these data is [204.2, 209.7], a 99 percent confidence interval is [203.4, 210.6], using $z_{.005} = 2.576$. The data support the conclusion that the specification is not met with 95 percent confidence, but the evidence is not so strong as to support this assertion with 99 percent confidence.

Scenario 1 (σ unknown): Consider now the somewhat more realistic situation that the population standard deviation of the tensile strengths is unknown. The preceding procedures apply with two modifications: First, the sample standard deviation s_y serves as a point estimator for σ and so replaces σ in the confidence intervals. Second, the critical value z_α is replaced by the critical value $t_{\alpha;n-1}$ obtained from Student's t distribution with $n - 1$ degrees of freedom (available in Table 11.1.4 or from statistical software). Thus, $\hat{\theta} = \bar{y}$, $s_{\hat{\theta}} = s_y/\sqrt{n}$, and $c_\alpha = t_{\alpha;n-1}$ in Eq. (1). Like the normal distribution, the t is symmetric and bell-shaped about zero, but it has fatter tails than the normal, meaning that $|t_{\alpha;n-1}| > |z_\alpha|$ so that the new $1 - \alpha$ level confidence intervals will be wider. Intuitively, because σ is unknown, the uncertainty is greater, so wider intervals are needed to achieve the same level of confidence. As the sample size n increases, however, s_y approaches σ, and likewise $t_{\alpha;n-1}$ converges to z_α so that these new intervals will approach those for σ known.

Given that $s_y = 8.2$ kg/cm^2 for the $n = 25$ tensile strength measurements and that $t_{.025;24} = 2.064$, the 95 percent two-sided confidence interval for μ is [204.1, 209.9], which is wider than the interval based on known $\sigma = 7$ kg/cm^2 (because both $s_y > 7$ and $t_{.025;24} > z_{.025}$), but falls just short of including the specification of $\mu = 210$ kg/cm^2.

Scenario 2: Let $X_1, X_2, \ldots, X_{n_A}$ and $Y_1, Y_2, \ldots, Y_{n_B}$ denote the tensile strength measurements for random samples of n_A and n_B blocks from the processes of manufacturers A and B, respectively. Model $X_i \sim N(\mu_A, \sigma_A^2)$, $i = 1, 2, \ldots, n_A$, and $Y_j \sim N(\mu_B, \sigma_B^2)$, $j = 1, 2, \ldots, n_B$, mutually independently. Then $\bar{X} \sim N(\mu_A, \sigma_A^2/n_A)$, $\bar{Y} \sim N(\mu_B, \sigma_B^2/n_B)$ and, moreover, $\bar{X} - \bar{Y} \sim N(\mu_A - \mu_B, \sigma_A^2/n_A + \sigma_B^2/n_B)$. Thus $\bar{X} - \bar{Y}$ serves as a point estimator for $\mu_A - \mu_B$, but, as before, the conclusion must incorporate the uncertainty about the true value of $\mu_A - \mu_B$ due to sampling variability.

Confidence intervals for $\mu_A - \mu_B$ depend on whether the population variances are assumed known. With σ_A^2 and σ_B^2 known and $\sigma_{\bar{X}-\bar{Y}} = (\sigma_A^2/n_A + \sigma_B^2/n_B)^{1/2}$, the $1 - \alpha$ confidence intervals for $\mu_A - \mu_B$ are given by Eq. (1) with $\hat{\theta} = \bar{x} - \bar{y}$, $s_{\hat{\theta}} = \sigma_{\bar{X}-\bar{Y}}$ and $c_\alpha = z_\alpha$.

Now suppose the data give $\bar{x} = 207$, $n_A = 25$, $\bar{y} = 210$, $n_B = 36$, and take $\sigma_A = 7$ and $\sigma_B = 8$, so that $\bar{x} - \bar{y} = -3$ kg/cm^2 and $\sigma_{\bar{X}-\bar{Y}} = 1.93$ kg/cm^2. The data support the conclusion that $\mu_B > \mu_A$, or $\mu_A - \mu_B < 0$, with confidence $1 - \alpha$ when a one-sided upper $1 - \alpha$ confidence interval for $\mu_A - \mu_B$ does not include zero. For $\alpha = 0.05$, the upper endpoint of this interval is $\bar{x} - \bar{y} + z_{.05}\sigma_{\bar{X}-\bar{Y}} = -3 + (1.645)(1.93) = 0.17$ kg/cm^2, implying the data do not support $\mu_B > \mu_A$ if 95 percent confidence is required. Recall, however, that lower confidence levels lead to narrower intervals—a relaxation to only 90 percent confidence does support $\mu_B > \mu_A$ (the upper endpoint is -0.53 kg/cm^2). The level of confidence required depends on the situation and is a subjective choice; values of 0.95 and 0.99 are common.

TABLE 11.1.4 Student's *t* Distribution Function

ν	$\alpha = .4$	$\alpha = .3$	$\alpha = .2$	$\alpha = .1$	$\alpha = .05$	$\alpha = .025$	$\alpha = .010$	$\alpha = .005$
1	0.325	0.727	1.376	3.078	6.314	12.706	31.821	63.657
2	0.289	0.617	1.061	1.886	2.920	4.303	6.965	9.925
3	0.277	0.584	0.978	1.638	2.353	3.182	4.541	5.841
4	0.271	0.569	0.941	1.533	2.132	2.776	3.747	4.604
5	0.267	0.559	0.920	1.476	2.015	2.571	3.365	4.032
6	0.265	0.553	0.906	1.440	1.943	2.447	3.143	3.707
7	0.263	0.549	0.896	1.415	1.895	2.365	2.998	3.499
8	0.262	0.546	0.889	1.397	1.860	2.306	2.896	3.355
9	0.261	0.543	0.883	1.383	1.833	2.262	2.821	3.250
10	0.260	0.542	0.879	1.372	1.812	2.228	2.764	3.169
11	0.260	0.540	0.876	1.363	1.796	2.201	2.718	3.106
12	0.259	0.539	0.873	1.356	1.782	2.179	2.681	3.055
13	0.259	0.538	0.870	1.350	1.771	2.160	2.650	3.012
14	0.258	0.537	0.868	1.345	1.761	2.145	2.624	2.977
15	0.258	0.536	0.866	1.341	1.753	2.131	2.602	2.947
16	0.258	0.535	0.865	1.337	1.746	2.120	2.583	2.921
17	0.257	0.534	0.863	1.333	1.740	2.110	2.567	2.898
18	0.257	0.534	0.862	1.330	1.734	2.101	2.552	2.878
19	0.257	0.533	0.861	1.328	1.729	2.093	2.539	2.861
20	0.257	0.533	0.860	1.325	1.725	2.086	2.528	2.845
21	0.257	0.532	0.859	1.323	1.721	2.080	2.518	2.831
22	0.256	0.532	0.858	1.321	1.717	2.074	2.508	2.819
23	0.256	0.532	0.858	1.319	1.714	2.069	2.500	2.807
24	0.256	0.531	0.857	1.318	1.711	2.064	2.492	2.797
25	0.256	0.531	0.856	1.316	1.708	2.060	2.485	2.787
26	0.256	0.531	0.856	1.315	1.706	2.056	2.479	2.779
27	0.256	0.531	0.855	1.314	1.703	2.052	2.473	2.771
28	0.256	0.530	0.855	1.313	1.701	2.048	2.467	2.763
29	0.256	0.530	0.854	1.311	1.699	2.045	2.462	2.756
30	0.256	0.530	0.854	1.310	1.697	2.042	2.457	2.750

Table entries are the critical values t_2; ν.

When the population variances are unknown, the form of the intervals is similar, but $\sigma_{\overline{X}-\overline{Y}}$ must be estimated, and z_α is replaced by a critical value from Student's *t* distribution. Estimation of $\sigma_{\overline{X}-\overline{Y}}$ and the degrees of freedom of the *t* distribution depend on whether it is reasonable to take $\sigma_A = \sigma_B$. Denote by s_A^2 and s_B^2 the sample variances of the data drawn from the processes of manufacturer A and B, respectively.

- When $\sigma_A = \sigma_B$, replace both σ_A^2 and σ_B^2 by

$$s_p^2 = [(n_A - 1)s_A^2 + (n_B - 1)s_B^2]/(n_A + n_B - 2)$$

and replace z_α by $t_{\alpha; n_A + n_B - 2}$. The level of the resulting confidence interval is exactly $1 - \alpha$ provided the populations are normal.

- When $\sigma_A \neq \sigma_B$, replace σ_A^2 by s_A^2, σ_B^2 by s_B^2, and z_α by $t_{\alpha;\upsilon}$, where the degrees of freedom are

$$\upsilon = \frac{(s_A^2/n_A + s_B^2/n_B)^2}{\dfrac{(s_A^2/n_A)^2}{n_A + 1} + \dfrac{(s_B^2/n_B)^2}{n_B + 1}} - 2$$

The confidence level of $1 - \alpha$ is approximate, even when the populations are normal.

The data from the processes of manufacturers A and B give $\bar{x} = 207$, $\bar{y} = 210$, $s_A = 8.2$, and $s_B = 10.7$ kg/cm^2 with $n_A = 25$ and $n_B = 36$. Assuming the population variances are equal, this common variance is estimated by $s_p^2 = 95.3$ (kg/cm^2)^2, giving an estimated standard deviation of 9.6 kg/cm^2. Using $t_{.05;\,59} = 1.67$, the upper endpoint of the 95 percent upper confidence interval for $\mu_A - \mu_B$ is $-3 + (1.67)(9.6)(1/25 + 1/36)^{1/2} = 1.17$ kg/cm^2, so these data do not support a greater mean tensile strength for manufacturer B at 95 percent confidence. Note that $t_{.05;\,59} = 1.67$ is very close to the normal critical value of $z_{.05} = 1.645$; this is because the degrees of freedom are very high (59), so the t distribution is very close to the normal.

If s_A is far from s_B then it may not be appropriate to assume the population variances are equal. (There is a statistical procedure for determining whether it is reasonable to assume that $\sigma_A = \sigma_B$; see Ref. 1, p. 177, and Ref. 6, p. 14.81.) If the sample sizes are large, however, meaning n_A and n_B are both about 30 or greater, then s_A and s_B will be close to σ_A and σ_B, respectively, and approximate $1 - \alpha$ confidence intervals can be formed using the procedure for known variances with s_A and s_B in place of σ_A and σ_B.

Permitting $\sigma_A \neq \sigma_B$ for manufacturers A and B, compute $\upsilon = 40.8$, which gives $t_{.05;\,40} = 1.684$. The right endpoint of the approximate 95 percent confidence interval for $\mu_A - \mu_B$ is $-3 + (1.684)[8.2^2/25 + 10.7^2/36]^{1/2} = 1.08$ kg/cm^2, again failing to support a greater mean tensile strength for manufacturer B.

Binomial Sampling: Example B

Let Y be the number of nonconforming piston rings in a random sample of size n from the process. As long as the probability that any piston ring is nonconforming is a constant p, say, and, within the sample, the quality of any particular piston ring does not affect the quality of any other, Y follows a binomial distribution with parameters n and p, written $Y \sim \text{Bin}(n, p)$. With this model, $E(Y) = np$, so a good point estimator for the *process* fraction nonconforming, p, is the *sample* fraction nonconforming $\hat{p} = Y/n$. Of course, under repeated sampling from the process, the observed value of Y, and hence of $\hat{p}$, will vary.

Confidence intervals can be used to reflect uncertainty about p due to the sampling variability. Because Y is a discrete variable, intervals that have exactly a specified confidence level generally do not exist. However, approximate $1 - \alpha$ level confidence intervals can be found using the normal distribution. This is because $Y = W_1 + W_2 + \ldots + W_n$, where W_i takes the value 1 if the ith piston ring is nonconforming and zero otherwise, so that Y and hence also $\hat{p}$ are approximately normally distributed by the central limit theorem. Approximate $1 - \alpha$ confidence intervals for p are given by Eq. (1), with $\hat{\theta} = \hat{p}$, $s_{\hat{\theta}} = \sqrt{\hat{p}(1 - \hat{p})/n}$ and $c_\alpha = z_\alpha$.

Scenario 1: To assess whether $p \leq 0.01$, suppose a random sample of $n = 500$ piston rings is obtained from the process and $y = 4$, so that $\hat{p} = 0.008$. Because the specification concerns an upper bound for p, a one-sided upper confidence interval for p is needed: if the $1 - \alpha$ level interval does not contain 0.01, it may be concluded that $p \leq 0.01$ with $1 - \alpha$ confidence. Here, the upper endpoint of the approximate 95 percent upper interval is 0.015. At 95 percent confidence, then, the process does not meet the specification.

Scenario 2: Let X and Y be the number of nonconforming piston rings found in random samples of size n_1 and n_2 taken from the process before and after the modification, respectively. Model $X \sim \text{Bin}(n_1, p_1)$ and $Y \sim \text{Bin}(n_2, p_2)$. Then $\hat{p}_1 = X/n_1$ and $\hat{p}_2 = Y/n_2$ are point estimators of p_1 and p_2, and $\hat{p}_1 - \hat{p}_2$ is approximately normally distributed with mean $p_1 - p_2$ and variance estimated by $\hat{p}_1(1 - \hat{p}_1)/n_1 + \hat{p}_2(1 - \hat{p}_2)/n_2$. Thus, approximate $1 - \alpha$ confidence intervals for $p_1 - p_2$ are given by Eq. (1), with $\hat{\theta} = \hat{p}_1 - \hat{p}_2$, $s_{\hat{\theta}} = \sqrt{\hat{p}_1(1 - \hat{p}_1)/n_1 + \hat{p}_2(1 - \hat{p}_2)/n_2}$ and $c_\alpha = z_\alpha$.

Take the observed data as $n_1 = 500$, $X = 4$, $n_2 = 300$, $Y = 2$. There is evidence of a process improvement if the data support $p_1 - p_2 > 0$. At 95 percent confidence, the lower endpoint of the lower interval for $p_1 - p_2$ is -0.0088, which does not support improvement.

THREE IMPORTANT MODELS

This section introduces three classes of methods that are especially useful for industrial engineers. These are reliability modeling, Shewhart control charts, and linear regression. The discussion of reliability also describes a graph useful for checking modeling assumptions called the *q-q* plot.

Reliability

Often in engineering it is of interest to model lifetime data, perhaps for the purpose of predicting failure times so that maintenance schedules can be optimized, for instance. Typically, lifetime data are markedly right skew, so the normal distribution is not an appropriate model. Instead, models such as the exponential and its generalizations, including the Weibull, have proven useful.

Example C: Twenty-five lightbulbs are randomly selected and tested until failure. Let Y_1, Y_2, . . . , Y_n be the lifetimes, with $n = 25$. The observed failure times (in days) are given in Table 11.1.5. A possible model is that the lifetimes are exponentially distributed with mean θ, which is the Weibull distribution with $\beta = 1$.

TABLE 11.1.5 Bulb Lifetimes (Days)

306.6	344.5	290.9	50.0	176.7
423.2	20.5	148.3	84.9	47.5
34.4	8.1	244.6	234.6	174.9
196.0	51.8	310.5	228.2	462.7
312.5	153.8	57.9	4.0	65.7

If the exponential model is correct, then θ is the mean lifetime for all bulbs, and so a natural point estimator for θ is the sample average of the observed lifetimes, $\overline{Y} = 177.3$ days. We know that $\mathrm{Var}(\overline{Y}) = \theta^2/n$ because θ^2 is the variance of a single observation from the exponential distribution. Thus, using approximate normality of $\overline{Y}$, an approximate 95 percent confidence interval for θ is $\overline{y} \pm z_{.025}\, \overline{y}/\sqrt{n}$, or [107.8, 246.8] days.

This result may be used to show, with approximately 95 percent confidence, that the probability of a randomly selected bulb from this process having a lifetime exceeding 300 days is between $1 - F_1(300) = 0.06$ and $1 - F_2(300) = 0.30$, where F_1 and F_2 are the cdf's for the exponential distributions with means 107.8 and 246.8, respectively. This prediction depends heavily on the assumption that the exponential distribution is the correct model.

One way to check whether the exponential distribution is reasonable is to construct a *quantile-quantile* or *q-q* plot. A *q-q* plot displays the quantiles of one distribution, often the sampled data, against the corresponding quantiles of another distribution, often the hypothesized model. For $Y \sim$ exponential with mean θ, $P(Y \le q) = 1 - e^{-q/\theta}$. So the pth quantile of the distribution of Y, q_p satisfies $q_p = -\theta \ln(1 - p)$. Now, an estimate of q_p is the pth sample quantile. From Table 11.1.2, the ith sorted observation, $y_{(i)}$, is the sample quantile of order $p_i = (i - 0.5)/n$. Thus, if the exponential model is correct, a plot of $y_{(i)}$ on $-\ln(1 - p_i)$, $i = 1, \dots, n$, should be close to a line with intercept zero and slope θ.

This plot is shown in Fig. 11.1.2 for the 25 lifetimes in this example, together with the line through the origin with slope 177.3. The line appears to fit the data well for the shorter lifetimes, with some deviation for the longer lifetimes, suggesting caution in interpreting results. In particular, it would not be advisable to rely on this model for predictions outside the range of these data—for example, to predict the probability of a lifetime exceeding 500 days. Such extrapolations are rarely reliable. This plot also provides a method for estimating θ: Simply estimate the slope of the plot either visually or by more advanced means such as linear regression, which will be explained shortly.

Another way to check whether the exponential model is reasonable is to fit a more general model, such as the Weibull, for which the exponential is a special case. Since the exponential is the Weibull with parameter $\beta = 1$, the simpler model may be appropriate if the estimated value of β is sufficiently close to one. A *q-q*-type plot can be constructed for the Weibull, which provides an exploratory investigation of whether β is close to 1. For $Y \sim$ Weibull (β, θ) and q_p the pth quantile of Y, it is straightforward to show that $\ln[-\ln(1-p)] = \beta \ln q_p - \beta \ln \theta$. Hence a plot of $\ln y_{(i)}$ on $\ln[-\ln(1-p_i)]$ will have slope β and intercept $-\beta\ln\theta$. This plot is shown in Fig. 11.1.3 for the 25 bulb lifetimes. Also shown is the line with intercept –5.2 and slope 1.0; because this line follows the data closely, it appears that the exponential model is sufficient. Indeed, more sophisticated estimation techniques yield an approximate 95 percent confidence interval for β of [0.57, 1.13], providing no evidence against the exponential model.

An important topic in modeling lifetimes is censoring, where, for example, the study is stopped before all failures have occurred. For methods appropriate in this situation, see Ref. 7.

Control Charts

An important use of statistics in industrial engineering is controlling a process. All processes have variability—for reasons as diverse as differences among machines, operators, and suppliers, variations in raw materials, changes in plant environment, and so on. Statistical process control methods help to distinguish between the variability inherent in a stable process, termed *common cause* variation, and that due to unexpected changes, called *special* or *assignable cause* variation. A stable process operating with only common cause variation is said to be *in control.* Otherwise, the process is called *out of control* because it additionally has special cause variation and assignable causes should be discovered and eliminated.

The variability in a process characteristic can be monitored by taking samples from the process at frequent intervals and measuring the characteristic on each item in the sample. A *control chart* is a time sequence plot of a summary statistic of the measurements from each sample, together with control limits that indicate an acceptable range of variation for the statistic. So

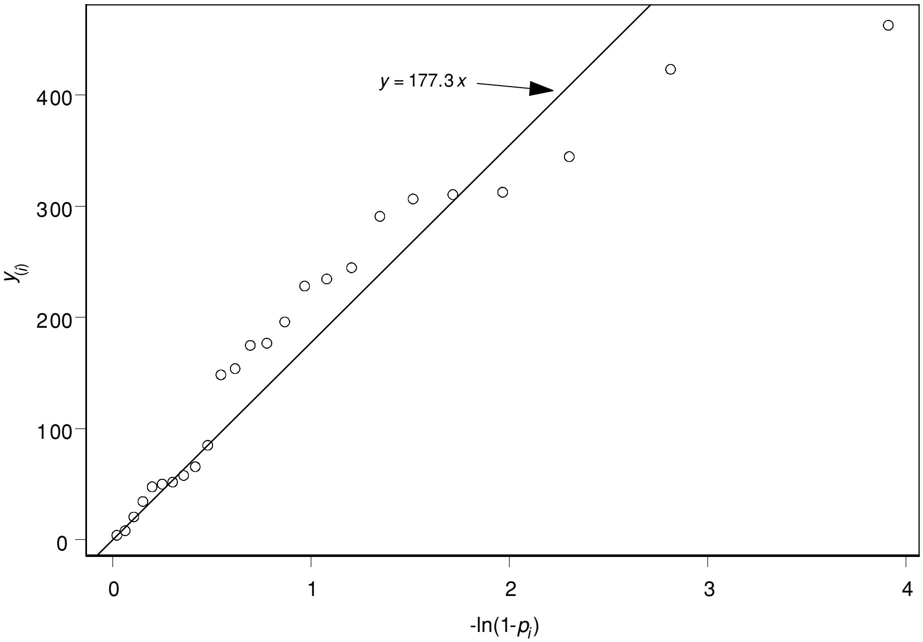

FIGURE 11.1.2 Exponential *q-q* plot for bulb lifetimes in Table 11.1.5.

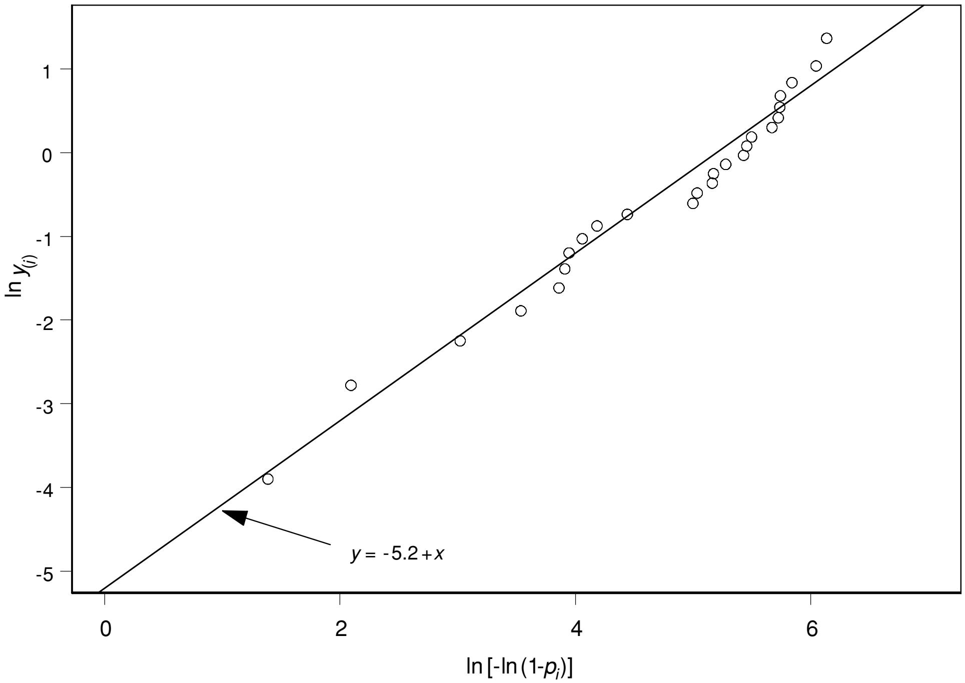

FIGURE 11.1.3 Weibull model plot for bulb lifetimes in Table 11.1.5.

long as the sample statistic plots within the control limits, no change should be made to the process—it is in control. A value plotting beyond the control limits, however, is an out-of-control signal and triggers action to remove any assignable cause.

To express the general idea, let Y be a random variable representing the process characteristic of interest. Usually, Y is an important quality indicator, such as the tensile strength of the rubber compound in Example A, or the piston ring process fraction nonconforming for Example B. At frequent intervals, a random sample $Y_1, Y_2, \ldots, Y_n$ is drawn from the process and summarized in a statistic $T = T(Y_1, Y_2, \ldots, Y_n)$. Typically T is the sample mean, $\overline{Y}$, or a measure of variability such as the range or sample standard deviation. The values of T are plotted sequentially versus sample number. If the process remains stable, the plotted values will exhibit regular variation around their mean, $E(T)$. The expected amount of variation depends on the standard deviation of T, σ_T.

Shewhart control charts* delimit the acceptable amount of variation as three standard deviations, typically, and hence place a centerline at $E(T)$ and control limits at $E(T) \pm 3\sigma_T$. This choice is well justified statistically because, for most distributions T might follow, an observed value outside this interval would be extremely rare when the process remains stable. Indeed, if T is normally distributed, the probability of a value more than three standard deviations from the mean is 0.0027, or about 1 in 370 values.

***$\overline{X}$* and *R* Charts.** It is important to monitor a continuous quality characteristic for changes in both mean and variability. To monitor the mean of Y, the $\overline{X}$ chart plots the average from each sample, $T = \overline{Y}$. (The name $\overline{X}$ chart comes from the common practice of denoting the qual-

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* Named for Dr. Walter A. Shewhart, who introduced the idea in the 1920s while at Bell Laboratories.

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ity characteristic by X rather than Y.) To monitor process variability, the R chart plots the sample ranges $T = \max Y_i - \min Y_i$.

Suppose the in-control process has mean $E(Y) = \mu_0$ and variance $\mathrm{Var}(Y) = \sigma_0^2$. Then the mean and variance of the average of a random sample of size n are $E(\overline{Y}) = \mu_0$ and $\mathrm{Var}(\overline{Y}) = \sigma_0^2/n$. Thus the centerline for the $\overline{X}$ chart is μ_0 and the lower and upper control limits are given by $\mathrm{LCL} = \mu_0 - 3\sigma_0/\sqrt{n}$ and $\mathrm{UCL} = \mu_0 + 3\sigma_0/\sqrt{n}$, respectively. Most often, however, μ_0 and σ_0 are unknown. In this case, a number of samples of size n, say k, are collected from what is likely to be a stable process (no change of shifts, raw materials, etc., during data collection) and used to estimate μ_0 and σ_0. If these k samples yield averages $\overline{y}_1, \overline{y}_2, \ldots, \overline{y}_k$ and ranges $R_1, R_2, \ldots, R_k$, the estimate of μ_0 is $\overline{\overline{y}} = \sum_{r=1}^{k} \overline{y}_i/k$ and the estimate of $3\sigma_0/\sqrt{n}$ is $A_2\overline{R}$, where $\overline{R}$ is the average of the k ranges and A_2 is a constant depending on n, available in Table 11.1.6. With these estimates, the $\overline{x}$ chart is set up with center line $\overline{\overline{y}}$ and control limits $\overline{\overline{y}} \pm A_2\overline{R}$ and used to monitor future production.

Though charts based on the sample standard deviation can be used to monitor variability, the R chart is a common choice because of the simplicity of computing ranges for plotting. The centerline of the R chart is estimated by $\overline{R}$ and the control limits are $\mathrm{LCL} = D_3\overline{R}$ and $\mathrm{UCL} = D_4\overline{R}$. The constants D_3 and D_4 are available in Table 11.1.6 and give three standard deviation control limits that have a very high probability of containing a sample range from a stable process.

Example D: Consider again the rubber compound process with tensile strength as the quality characteristic. To set up control charts, $k = 10$ preliminary samples of size $n = 5$ were obtained from the stable process, yielding sample averages and ranges for the tensile strength as shown in Table 11.1.7. For these values, $\overline{\overline{y}} = 210.7$ kg/cm^2 and $\overline{R} = 15.6$ kg/cm^2, so that the center line for the $\overline{x}$ chart is 210.7 kg/cm^2 and the control limits are $210.7 \pm (0.577)(15.6)$, or $\mathrm{LCL} = 201.7$ and $\mathrm{UCL} = 219.7$ kg/cm^2, where $A_2 = 0.577$ for $n = 5$. For the R chart, the cen-

TABLE 11.1.6 Factors for Determining the 3σ Control Limits in $\overline{X}$ and R Charts

Number of observations in sample, n	A_2	D_3	D_4
2	1.88	0	3.27
3	1.02	0	2.57
4	0.73	0	2.28
5	0.58	0	2.11
6	0.48	0	2.00
7	0.42	0.08	1.92
8	0.37	0.14	1.86
9	0.34	0.18	1.82
10	0.31	0.22	1.78
11	0.29	0.26	1.74
12	0.27	0.28	1.72
13	0.25	0.31	1.69
14	0.24	0.33	1.67
15	0.22	0.35	1.65
16	0.21	0.36	1.64
17	0.20	0.38	1.62
18	0.19	0.39	1.61
19	0.19	0.40	1.60
20	0.18	0.41	1.59

Source: Reproduced and adapted with permission from Hogg and Ledolter, *Applied Statistics for Engineers and Scientists,* 2d ed., 1992.

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TABLE 11.1.7 Data for Tensile Strength Control Charts

$\bar{y}$	209.7	211.6	212.2	208.4	210.2	210.5	210.8	208.9	211.4	213.5
R	11.7	12.0	17.5	21.4	15.6	22.4	13.0	8.2	15.2	18.9

ter line is $\overline{R} = 15.6$ and, since $D_3 = 0$ and $D_4 = 2.115$ for $n = 5$, the control limits are LCL = 0 and UCL = 33.0 kg/cm^2. For sample sizes of 6 or less, the lower control limit for an R chart will be zero; because ranges must be positive, then, a reduction in process variability cannot be detected using the R chart unless larger sample sizes are selected.

Figure 11.1.4 shows the $\overline{X}$ and R charts for 15 new samples drawn from production. The R chart gives no indication of any change in variability, but the out-of-control alarm for sample number 12 on the $\overline{X}$ chart indicates that the mean tensile strength may have changed. Once the 12th sample average plotted beyond the UCL, assignable causes should have been sought and removed.

p Chart. When each item is checked on only a pass-fail basis regarding whether it conforms to specifications or not, the p chart can be used to monitor the underlying process fraction nonconforming. To set up the chart, k samples of size n are collected at regular intervals when the process is believed to be stable. Letting y_i be the number of nonconforming items in sample i, $\bar{p} = \sum_{i=1}^{k} y_i/(nk)$ is an estimate of the in-control (stable) process fraction nonconforming. Assuming the process remains stable, the fraction nonconforming in new samples of size n drawn from production, $\hat{p} = y/n$, will have approximate mean $\bar{p}$ and variance $\bar{p}(1 - \bar{p})/n$. Hence, almost all values of $\hat{p}$ that would be observed in future production will be between the control limits $\bar{p} \pm 3\sqrt{\bar{p}(1 - \bar{p})/n}$. These control limits, together with the centerline $\bar{p}$, are drawn on a chart, and the fractions nonconforming in new samples are plotted. Fractions outside the control limits suggest that the underlying process proportion nonconforming has changed. Particularly, fractions above the UCL indicate a deterioration of the process, and fractions below the LCL indicate possible improvement. In either case, explanation should be found, in the first case to remedy the situation and in the second case to understand a potential process enhancement.

Example E: Every hour $n = 50$ piston rings are randomly selected from production and tested. For the first $k = 20$ hours the total number of nonconforming piston rings is 20. Thus $\bar{p} = 20/1000 = 0.02$ and the control limits are $0.02 \pm 3\sqrt{(0.02)(0.98)/50}$, which gives LCL = –0.039 and UCL = 0.079. Because LCL < 0 and no $\hat{p}$ can be less than zero, the lower control limit is taken to be LCL = 0 in this example. Figure 11.1.5 shows the p chart for these 20 hours of production together with the next 7 hours. Because of the out-of-control signal at the 7th new sample, the process was investigated and corrective action taken.

There are many more control charts and other statistical methods important in process control; please see Ref. 8.

Linear Regression

An important problem in engineering is determining the effect, if any, that input variables have on a process response. An extremely useful tool for this problem is regression analysis, which models a response Y as a function of explanatory variables (also called *predictors*) $x_1, x_2, \ldots, x_p$. This section describes linear regression, for which a linear relationship is postulated between Y and the predictors. This linearity assumption is not so restrictive as it may seem, because the predictors and/or Y may be transformed. For example, it may not be appropriate to model yield as linearly dependent on temperature, but rather as linearly dependent on the logarithm of temperature.

The linear regression model takes the form $y = f(\mathbf{x}) + \varepsilon$, as discussed earlier in this chapter,

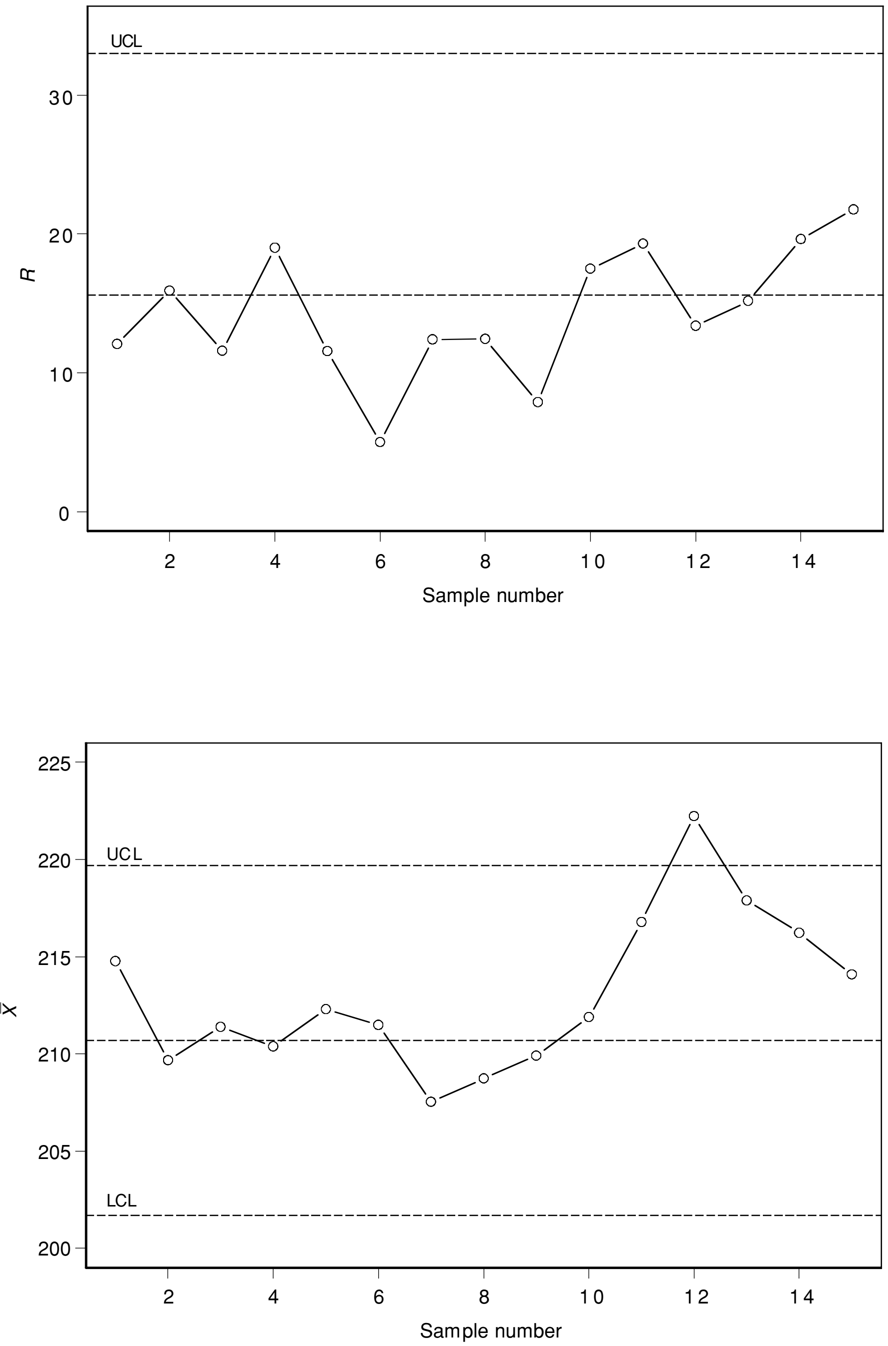

FIGURE 11.1.4 $\overline{X}$ and R charts for the tensile strength data in Table 11.1.7.

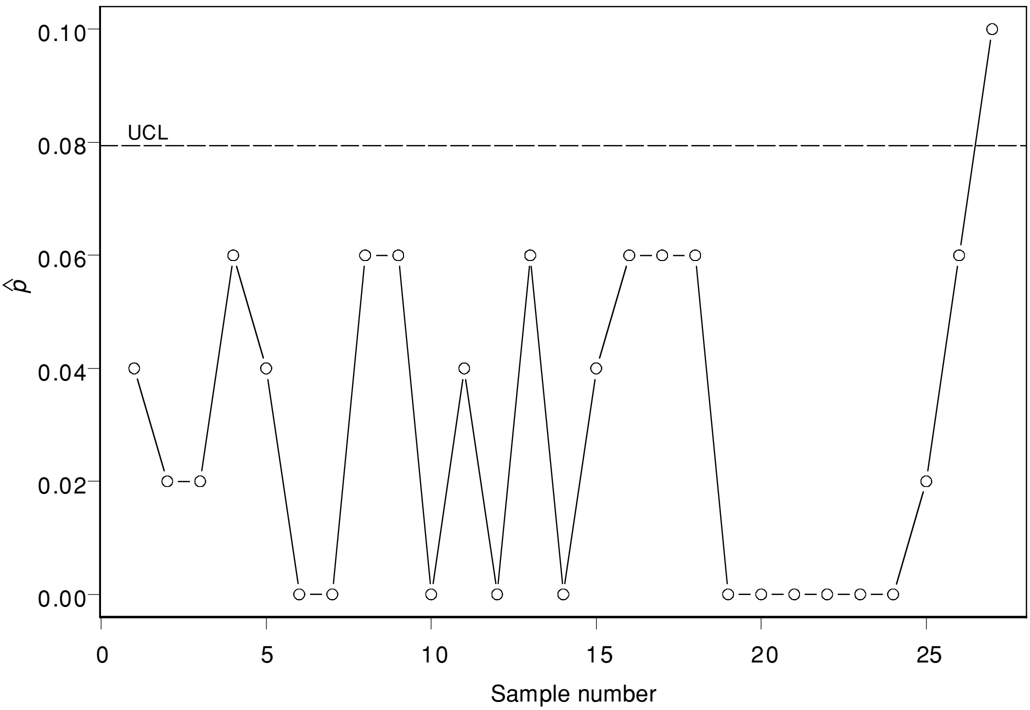

FIGURE 11.1.5 *p* chart for piston process data.

where $f(\mathbf{x})$ is linear:

$$Y_i = \beta_0 + \beta_1 x_{i1} + \beta_2 x_{i2} + \ldots + \beta_p x_{ip} + \varepsilon_i \qquad i = 1, 2, \ldots, n \tag{11.1.2}$$

Here Y_i is the random variable representing the response value when the input variables are set to $(x_{i1}, x_{i2}, \ldots, x_{ip})$, the coefficients $\beta_0, \beta_1, \ldots, \beta_p$ are unknown parameters to be estimated, and the error ε_i is a random variable assumed to have mean zero and unknown variance σ^2, $i = 1, 2, \ldots, n$. Thus $E(Y_i) = \beta_0 + \beta_1 x_{i1} + \beta_2 x_{i2} + \ldots + \beta_p x_{ip}$, and $\text{Var}(Y_i) = \sigma^2$, $i = 1, 2, \ldots, n$. The intercept is β_0 and each β_j, $j = 1, 2, \ldots, p$, is a slope coefficient giving the change in the expected value of Y when predictor x_j is increased by one unit. The variance of the errors, σ^2, represents the variability in Y that cannot be explained by the linear combination of predictors.

To simplify notation, write Eq. (2) as $\mathbf{Y} = \mathbf{X}\boldsymbol{\beta} + \boldsymbol{\varepsilon}$, where $\mathbf{Y} = (Y_1, Y_2, \ldots, Y_n)^T$ is the $n \times 1$ vector of response values; $\mathbf{X}$ is the $n \times (p + 1)$ matrix with first column the vector of 1s and remaining columns the vectors of predictors $\mathbf{x}_j = (x_{1j}, x_{2j}, \ldots, x_{nj})^{\mathbf{T}}$; $\boldsymbol{\beta} = (\beta_0, \beta_1, \ldots, \beta_p)^{\mathbf{T}}$ is the $(p + 1) \times 1$ vector of regression coefficients, including the intercept; and $\boldsymbol{\varepsilon} = (\varepsilon_1, \varepsilon_2, \ldots, \varepsilon_n)^{\mathbf{T}}$ is the $n \times 1$ vector of errors.

Estimation is performed using the *least squares* criterion, under which the estimator $\hat{\boldsymbol{\beta}}$ of $\boldsymbol{\beta}$ is chosen to minimize the distance between the observed value of $\mathbf{Y}$ and its expectation under the model. Thus $\hat{\boldsymbol{\beta}}$ is the argument that minimizes

$$S(\boldsymbol{\beta}) = \|\mathbf{y} - \mathbf{X}\boldsymbol{\beta}\|^2 = \sum_{i=1}^{n} (y_i - [\beta_0 + \beta_1 x_{i1} + \ldots + \beta_p x_{ip}])^2$$

The solution is easily obtained using calculus and is

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$$\hat{\boldsymbol{\beta}} = (\mathbf{X}^{\mathrm{T}}\mathbf{X})^{-1}\mathbf{X}^{\mathrm{T}}\mathbf{y} \tag{11.1.3}$$

as long as $(\mathbf{X}^{\mathrm{T}}\mathbf{X})^{-1}$ exists. The *fitted* or *predicted* values of $\mathbf{Y}$ are

$$\hat{\mathbf{y}} = \mathbf{X}\hat{\boldsymbol{\beta}} = \mathbf{X}(\mathbf{X}^{\mathrm{T}}\mathbf{X})^{-1}\mathbf{X}^{\mathrm{T}}\mathbf{y}$$

and the *residuals* are $\mathbf{r} = \mathbf{y} - \hat{\mathbf{y}}$. The estimator of σ^2 is

$$\hat{\sigma}^2 = \|\mathbf{r}\|^2/[n - (p+1)] = S(\hat{\boldsymbol{\beta}})/[n - (p+1)]$$

Example F (simple linear regression): The density of a polymer is known to depend on the annealing temperature. Within the range of annealing temperatures of practical interest, a linear model is a good approximation to the true relationship. Polymer was annealed at 10 different temperatures and times and the density recorded for each, giving the results in Table 11.1.8. Consider the model

$$Y_i = \beta_0 + \beta_1 x_i + \varepsilon_i \tag{11.1.4}$$

where x_i is the ith annealing temperature and Y_i is the corresponding density measurement. Because there is just $p = 1$ explanatory variable, Eq. (4) is called the *simple linear regression* model. In this case, letting $SXX = \sum_{i=1}^{n}(x_i - \bar{x})^2$ and $SXY = \sum_{i=1}^{n}(x_i - \bar{x})(y_i - \bar{y})$, (3) simplifies to

$$\hat{\beta}_1 = SXY/SXX \qquad \text{and} \qquad \hat{\beta}_0 = \bar{y} - \hat{\beta}_1\bar{x}$$

The polymer data give $\hat{\beta}_0 = -19.1$ g/ml and $\hat{\beta}_1 = 0.77$ (g/ml)/°C, so that, for annealing temperatures between 146 and 234°C, the polymer density increases by 0.77 g/ml for each degree increase in temperature, on average. The fitted line suggests that annealing at temperatures below 24°C will produce polymers with negative densities! This ridiculous result again illustrates the dangers of extrapolating beyond the range of data used in the analysis.

Confidence Intervals for Regression Parameters. Confidence intervals are formed for the regression parameter β_j using (1) with $\hat{\theta} = \hat{\beta}_j$, $c_\alpha = t_{\alpha;n-(p+1)}$ and $s_{\hat{\theta}} = \hat{\sigma}\sqrt{(\mathbf{X}^{\mathrm{T}}\mathbf{X})^{-1}_{jj}}$. The $1 - \alpha$ confidence level of this interval depends upon the additional assumption that the errors ε_i are normally distributed; if this is not the case, then the interval has only approximately $1 - \alpha$ confidence of covering β_j. This interval is formed for β_j in the context of the other predictors in the model, but should be interpreted in isolation from confidence intervals for other regression parameters. In particular, although a collection of $1 - \alpha$ confidence intervals can be formed, one for each β_j, $j = 1, \ldots, p$, the confidence level associated with these intervals simultaneously containing their respective parameters is likely to be substantially less than $1 - \alpha$. See Ref. 8 for methods for forming simultaneous intervals or p-dimensional confidence regions that have a known confidence.

Prediction Intervals. There are two interpretations for the fitted response, $\hat{y}(\mathbf{x})$, at a given $1 \times (p+1)$ set of predictors $\mathbf{x}$. The first is as a prediction for a single response value, $Y(\mathbf{x})$, that might be observed at $\mathbf{x}$. The second interpretation for $\hat{y}(\mathbf{x})$ is as an estimate of $\mathrm{E}[Y(\mathbf{x})]$, the mean of all response values that might be observed at this $\mathbf{x}$. The uncertainty is greater in the

TABLE 11.1.8 Polymer Density Data

Annealing time (min)	4.0	9.7	34.4	23.3	50.5	38.0	41.2	43.4	61.0	56.4
Annealing temperature (°C)	146	149	165	179	195	197	209	222	223	234
Polymer density (g/ml)	100.3	91.1	100.3	114.9	142.7	138.7	149.7	136.6	165.1	155.8

first case and, hence, although the point estimates are equal, interval estimates at the same level of confidence will be wider for $Y(\mathbf{x})$ than for $E[Y(\mathbf{x})]$. These confidence intervals are as follows:

- For $Y(\mathbf{x})$, use Eq. (1) with $\hat{\theta} = \hat{y}(\mathbf{x})$, $c_\alpha = t_{\alpha;n-(p+1)}$ and $s_{\hat{\theta}} = \hat{\sigma}\sqrt{1 + \mathbf{x}(\mathbf{X}^{\mathbf{T}}\mathbf{X})^{-1}\mathbf{x}^{\mathbf{T}}}$
- For $E[Y(\mathbf{x})]$, use Eq. (1) with $\hat{\theta} = \hat{y}(\mathbf{x})$, $c_\alpha = t_{\alpha;n-(p+1)}$ and $s_{\hat{\theta}} = \hat{\sigma}\sqrt{\mathbf{x}(\mathbf{X}^{\mathbf{T}}\mathbf{X})^{-1}\mathbf{x}^{\mathbf{T}}}$

These intervals have exact $1 - \alpha$ coverage when Y is normally distributed and are approximate otherwise.

Example F (continued): Fitting Eq. (4) to the polymer density data with annealing temperature as predictor gives $\hat{\sigma}^2 = \sum_{i=1}^{n}(y_i - \hat{y}_i)^2/(n-2) = 98.3$, or $\hat{\sigma} = 9.9$ g/ml. The diagonal elements of $(\mathbf{X}^{\mathbf{T}}\mathbf{X})^{-1}$ are (4.3, 1.0E-4). Thus, using $t_{.05;8} = 1.86$ and assuming the polymer density is normally distributed, a 90 percent two-sided confidence interval for the slope is $0.77 \pm (1.86)(9.9)(0.01) = (0.59, 0.95)$. This interval indicates that the annealing temperature is a useful predictor for the polymer density, since the data support that β_1 is nonzero. A 90 percent two-sided interval for the intercept is $-19.1 \pm (1.86)(9.9)(4.3)^{1/2} = (-57.3, 19.1)$, so the data do not support a nonzero intercept. (One may wish to consider constraining $\beta_0 = 0$ in Eq. (4), and this is straightforward, but will not be pursued here.)

Suppose now that it is desired to estimate the mean density of all polymers annealed at 200°C, $E[Y(x = 200)]$. The point estimate is $\hat{y}(200) = -19.1 + 0.77(200) = 135.8$ g/ml. At 200°C, $\mathbf{x} = (1\ 200)$, and $\mathbf{x}(\mathbf{X}^{\mathbf{T}}\mathbf{X})^{-1}\mathbf{x}^{\mathbf{T}} = 0.11$, so that a 90 percent two-sided confidence interval for $E[Y(x = 200)]$ is $135.8 \pm (1.86)(9.9)(0.11)^{1/2} = (129.7, 141.9)$ g/ml. If the density of a single polymer annealed at 200°C is of interest, however, then the uncertainty is greater, and the confidence interval for $Y(x = 200)$ is $135.8 \pm (1.86)(9.9)(1 + 0.11)^{1/2} = (116.4, 155.2)$ g/ml.

Example G (multiple linear regression): The annealing time, also given in Table 11.1.8, is another potential predictor of the polymer density. Letting x_1 and x_2 be the annealing temperature and time, respectively, the regression model in Eq. (2) yields least squares estimates $\hat{\beta}_0 = 9.5$ g/ml, $\hat{\beta}_1 = 0.55$ g/ml/°C, and $\hat{\beta}_2 = 0.42$ g/ml/min. The estimate of the error standard deviation is $\hat{\sigma} = 9.9$ g/ml. Notice that including annealing time in the model has changed the estimated coefficient for annealing temperature; this is to be expected because the estimates are obtained in the context of the predictors in the model. Intuitively, x_2 explains some of the variability in Y, and so its inclusion in the model may cause x_1 to have more or less explanatory power for the remaining variability in Y. The diagonal elements of $(\mathbf{X}^{\mathbf{T}}\mathbf{X})^{-1}$ are (12.2, 6.1E-4, 1.2E-03), and $t_{.05;7} = 1.89$. Thus a 90 percent confidence interval for β_2 is $0.42 \pm (1.89)(9.9)(0.04) = (-0.35, 1.2)$. With annealing temperature in the model, annealing time does not contribute significantly to explaining the polymer density. The 90 percent confidence interval for β_1 is $0.55 \pm (1.89)(9.9)(0.02) = (0.08, 1.0)$, which does not cover zero, so that annealing temperature retains its utility.

Model Checking. Before relying on conclusions about parameters or predicted values, it is important to assess the model assumptions. These are the linearity of the relationship between Y and the predictors and the normality, independence, and constant variance of the errors. Simple graphs can be constructed that often reveal any existing departures from these assumptions. For example, a quadratic pattern in a plot of the residuals versus a predictor x_j, say, suggests that including x_j^2 as a new predictor in the model may improve the fit. Similarly, a fanning or megaphone shape in a plot of the residuals versus the fitted values suggests that the variance of the errors increases with the magnitude of Y, thus violating the constant variance assumption. Space limitations prevent illustration of these and other graphs, but please see Refs. 10 and 11 for details and examples. Of course, the model is only a useful approximation to the real-world process; as the statistician G. E. P. Box said, "All models are wrong but some are useful." The regression model has been extended to accommodate a wide variety of departures from these assumptions; see, for example, Refs. 12 and 13.

Two-Level Factorial Designs. In the preceding polymer example, it is not clear how the

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TABLE 11.1.9 Yields (mg) for the Chemical Reaction with Temperature (T) and Reactant Concentration (C) as Given

		T	
		120°	160°
C	1%	27, 33	21, 17
	5%	41, 33	22, 18

annealing temperatures and times were chosen for the purposes of the data collection. In *experimental design,* the values of the predictor variables at which the response will be observed are determined in advance to aid interpretation of the regression parameters. A particularly simple and powerful experimental design is the two-level factorial, for which the response is observed at all combinations of several predictors, each at two values, or *levels.* These are commonly termed 2^k designs because, with k predictors each at two levels, the experiment requires a minimum of 2^k observations.

Example H: The yield of a chemical reaction depends on the reactant concentration and temperature. To study these effects, low and high levels of reactant concentration ($C = 1\%$ and 5%) and temperature ($T = 120°$ and $160°$) were chosen and the reaction was run twice at each combination. The order of the runs was randomized to minimize any effects due to unforeseen factors such as weariness of the chemist or variations in laboratory humidity. These data are shown in Table 11.1.9.

It is customary in 2^k experiments to code the low and high factor levels as -1 and $+1$, respectively. Thus, let $x_1 = (C - 3)/2$ and $x_2 = (T - 140)/20$. The data can be analyzed using the linear regression model in Eq. (2), with predictors x_1, x_2 and $x_3 = x_1x_2$. Inclusion of x_3 permits the effect of x_1 to depend on the level of x_2; the slope associated with x_1 is $\beta_1 - \beta_3$ when $x_2 = -1$, but is $\beta_1 + \beta_3$ when $x_2 = +1$. The coefficient β_3 is called the *interaction effect* of reactant concentration and temperature on yield, while β_1 and β_2 are called *main effects* of these factors.

The least squares estimates are $\hat{\beta}_0 = 26.5$, $\hat{\beta}_1 = 2.0$, $\hat{\beta}_2 = -7.0$, $\hat{\beta}_3 = -1.5$, with $\hat{\sigma} = 4.1$ mg. Thus, each 2 percent increase in reactant concentration seems to increase the average yield by 2 mg, whereas each 20° increase in temperature decreases the average yield by 7 mg. The negative interaction effect suggests that the effect of increasing reactant concentration when temperature is low is greater than this effect when temperature is high. The key, however, is the size of these effects relative to the variability in the data. A change of 4 mg or less in yield is likely not important, as this occurs just by chance when temperature and reactant concentration remain fixed! To construct confidence intervals for the true effects, note that $(\mathbf{X}^\mathbf{T}\mathbf{X})^{-1} = 0.125\mathbf{I}_4$, where $\mathbf{I}_4$ is the 4×4 identity matrix. Thus, the 90 percent interval has half width $t_{.05;\,4}\hat{\sigma}(0.125)^{1/2} = (2.13)(4.1)(0.35) = 3.1$ for all parameters, and only the intercept β_0 and the main effect of temperature β_2 are different from zero at 90 percent confidence.

Although this example has illustrated only the 2^2 design, the concepts and calculations are easily extended to the general 2^k experiment (see, for example, Ref. 14). The special structure of the $\mathbf{X}$ matrix, the experimental design, caused all regression parameter estimates to have the same estimated variance. Another simplification resulting from the structure of 2^k designs is that the parameter estimates are especially easy to compute. In particular, $\hat{\beta}_0$ is the grand average of all response values, and $\hat{\beta}_j$ is one-half the difference in average response between the high and low levels of x_j, where $x_3 = x_1x_2$. The interaction effect $\hat{\beta}_3$ is also one-half the difference between the main effect of x_1 when x_2 is high and the main effect of x_1 when x_2 is low. Moreover, the structure of 2^k designs implies that the parameter estimates do not change when design factors, such as reactant concentration in this example, are removed from the model. For these and many more reasons, experimental design, including at least the 2^k design, is an important technique for the industrial engineer.

ADDITIONAL TECHNIQUES

Statistical analyses are becoming increasingly computationally intensive due to the large amounts of data available and the prevalence of high-powered computing. Most statistical analyses are performed using statistical software—there are many very good packages that compute needed quantities in numerically stable ways.

Statistical methods for very large data sets include visualization, principal components, factor analysis, and other methods for multivariate data [15], and these techniques make up a large part of modern data mining.

It is often difficult to derive the exact distribution on which to base inferences for more complicated statistical models. Hence, many modern statistical analyses, particularly those using Bayesian methods [16], rely heavily on Monte Carlo simulation [17,18]. More generally, simulation models [19] are powerful tools for understanding and improving complex manufacturing processes.

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BIOGRAPHY

Elizabeth H. Slate obtained her Ph.D. in statistics from Carnegie Mellon University in Pittsburgh, Pennsylvania. From there, she joined the faculty in the School of Operations Research and Industrial Engineering at Cornell University in Ithaca, New York. She wrote this chapter while an associate professor at Cornell. Dr. Slate has since joined the Department of Biometry and Epidemiology at the Medical University of South Carolina, Charleston, South Carolina.

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CHAPTER 11.2

PRINCIPLES AND APPLICATIONS OF OPERATIONS RESEARCH

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This chapter will provide an overview of operations research (OR) from the perspective of an industrial engineer. The focus of the chapter is on the basic philosophy behind OR and the so-called OR approach to solving design and operational problems that industrial engineers commonly encounter. In its most basic form, OR may be viewed as a scientific approach to solving problems; it abstracts the essential elements of the problem into a *model,* which is then analyzed to yield an optimal solution for implementation. The mathematical details and the specific techniques used to build and analyze these models can be quite sophisticated and are addressed elsewhere in this handbook; the emphasis of this chapter is on the *approach.* A brief review of the historical origins of OR is followed by a detailed description of its methodology. The chapter concludes with some examples of successful real-world applications of OR.

INTRODUCTION

Although it is a distinct discipline in its own right, operations research (OR) has also become an integral part of the industrial engineering (IE) profession. This is hardly a matter of surprise when one considers that they both share many of the same objectives, techniques, and application areas. OR as a formal discipline is about 50 years old and its origins may be traced to the latter half of World War II. Most of the OR techniques that are commonly used today were developed over (approximately) the first 20 years following its inception. During the next 30 or so years the pace of development of fundamentally new OR methodologies slowed somewhat. However, there was a rapid expansion in (1) the breadth of problem areas to which OR can be applied, and (2) in the magnitude of the problems that can be addressed using OR methodologies. Today, operations research is a mature, well-developed field with a sophisticated array of techniques that are used routinely to solve problems in a wide range of application areas.

This chapter will provide an overview of OR from the perspective of an industrial engineer. A brief review of its historical origins is first provided. This is followed by a detailed discussion of the basic philosophy behind OR and the OR approach. The chapter concludes with several examples of successful applications to typical problems that might be faced by an industrial engineer. Broadly speaking, an OR project comprises three steps: (1) building a model, (2) analyzing it, and (3) implementing the results. The emphasis of this chapter is on the first and third steps. The second step typically involves specific methodologies or techniques, which can be quite sophisticated and require significant mathematical development. Several important methods are reviewed elsewhere in this handbook. The reader who has an interest in learning more about these topics is referred to one of the many excellent texts on OR that are available today and that are listed under Further Reading at the end of this chapter.

A HISTORICAL PERSPECTIVE

While there is no clear date that marks the birth of OR, it is generally accepted that the field originated in England during World War II. The impetus for its origin was the development of radar defense systems for the Royal Air Force, and the first recorded use of the term *operations research* is attributed to a British Air Ministry official named A. P. Rowe who constituted teams to do "operational researches" on the communication system and the control room at a British radar station. The studies had to do with improving the operational efficiency of systems (an objective that is still one of the cornerstones of modern OR). This new approach of picking an operational system and conducting research on how to make it run more efficiently soon started to expand into other arenas of the war. Perhaps the most famous of the groups involved in this effort was the one led by a physicist named P. M. S. Blackett and included physiologists, mathematicians, astrophysicists, and even a surveyor. This multifunctional team focus of an operations research project group has carried forward to this day. Blackett's biggest contribution was in convincing the authorities of the need for a scientific approach to manage complex operations, and indeed he is regarded in many circles as the original operations research analyst.

OR made its way to the United States a few years after it originated in England. Its first presence in the United States was through the U.S. Navy's Mine Warfare Operations Research Group; this eventually expanded into the Antisubmarine Warfare Operations Research Group that was led by Phillip Morse, which later became known simply as the Operations Research Group. Like Blackett in Britain, Morse is widely regarded as the father of OR in the United States, and many of the distinguished scientists and mathematicians that he led went on after the end of the war to become the pioneers of OR in the United States.

In the years immediately following the end of World War II, OR grew rapidly as many scientists realized that the principles that they had applied to solve problems for the military were equally applicable to many problems in the civilian sector. These ranged from short-term problems such as scheduling and inventory control to long-term problems such as strategic planning and resource allocation. George Dantzig, who in 1947 developed the simplex algorithm for linear programming (LP), provided the single most important impetus for this growth. To this day, LP remains one of the most widely used of all OR techniques and despite the relatively recent development of interior point methods as an alternative approach, the simplex algorithm (with numerous computational refinements) continues to be widely used. The second major impetus for the growth of OR was the rapid development of digital computers over the next three decades. The simplex method was implemented on a computer for the first time in 1950, and by 1960 such implementations could solve problems with about 1000 constraints. Today, implementations on powerful workstations can routinely solve problems with hundreds of thousands of variables and constraints. Moreover, the large volumes of data required for such problems can be stored and manipulated very efficiently.

Once the simplex method had been invented and used, the development of other methods followed at a rapid pace. The next 20 years witnessed the development of most of the OR techniques that are in use today, including nonlinear, integer, and dynamic programming, computer simulation, the program evaluation and review technique (PERT) and the critical path method (CPM), queuing theory, inventory models, game theory, and sequencing and scheduling algorithms. The scientists who developed these methods came from many fields, most notably mathematics, engineering, and economics. It is interesting that the theoretical bases for many of these techniques had been known for years; for example, the economic order quantity (EOQ) formula used with many inventory models was developed in 1915 by F. W. Harris, and many of the queuing formulas were developed by A. K. Erlang in 1917. However, the period from 1950 to 1970 was when these were formally unified into what is considered the standard toolkit for an operations research analyst and successfully applied to problems of industrial significance. The following section describes the approach taken by operations research to solve problems and explores how all of these methodologies fit into the OR framework.

WHAT IS OPERATIONS RESEARCH?

A common misconception held by many is that OR is a collection of mathematical tools. While it is true that it uses a variety of mathematical techniques, operations research has a much broader scope. It is a systematic approach to solving problems, which uses one or more analytical tools in the process of analysis. Perhaps the single biggest problem with OR is its name: to a layperson, the term *operations research* does not conjure up any sort of meaningful image! This is an unfortunate consequence of the fact that the name that A. P. Rowe is credited with first assigning to the field was somehow never altered to something that is more indicative or descriptive of the things that OR actually does. Sometimes OR is referred to as management science (MS) to better reflect its role as a scientific approach to solving management problems, but it appears that this terminology is more popular with business professionals and people still quibble about the differences between OR and MS. Compounding this is the lack of a clear consensus on a formal definition for OR. For instance, C. W. Churchman, who is considered one of the pioneers of OR, defined it as "the application of scientific methods, techniques and tools to problems involving the operations of a system so as to provide those in control of the system with optimum solutions to problems." This is indeed a rather comprehensive definition, but there are many others who tend to go to the other extreme and define operations research to be simply *that which operations researchers do* (a definition that seems to be most often attributed to E. Naddor). Regardless of the exact words used, it is probably safe to say that the moniker *operations research* is here to stay, and it is therefore important to understand that in essence OR may simply be viewed as a *systematic and analytical approach to decision making and problem solving.* The key here is that OR uses a methodology that is objective and clearly articulated, and is built around the philosophy that such an approach is superior to one that is based purely on subjectivity and the opinion of experts, in that it will lead to better and more consistent decisions. However, OR does *not* preclude the use of human judgement or nonquantifiable reasoning; rather, the latter are viewed as being complementary to the analytical approach. One should thus view OR not as an absolute decision-making process, but as an *aid* to making good decisions. OR plays an advisory role by presenting a manager or a decision maker with a set of sound, scientifically derived alternatives. However, the final decision is always left to the human being who has knowledge that cannot be exactly quantified and who can temper the results of the analysis to arrive at a sensible decision.

THE OPERATIONS RESEARCH APPROACH

Given that OR represents an integrated framework to help make decisions, the next step is to have a clear understanding of this framework so that it can be applied to a generic problem. To achieve this, the OR approach is now detailed. This approach comprises the following seven sequential steps: (1) orientation, (2) problem definition, (3) data collection, (4) model formulation, (5) solution, (6) model validation and output analysis, and (7) implementation and monitoring. Tying each of these steps together is a mechanism for continuous feedback;

the overall approach may be viewed schematically as shown in Fig. 11.2.1. While most of the academic emphasis has been on steps 4, 5, and 6, the reader should bear in mind that the other steps are equally important from a practical perspective. Indeed, insufficient attention to these steps has been the reason why OR has sometimes been mistakenly considered impractical or ineffective in the real world.

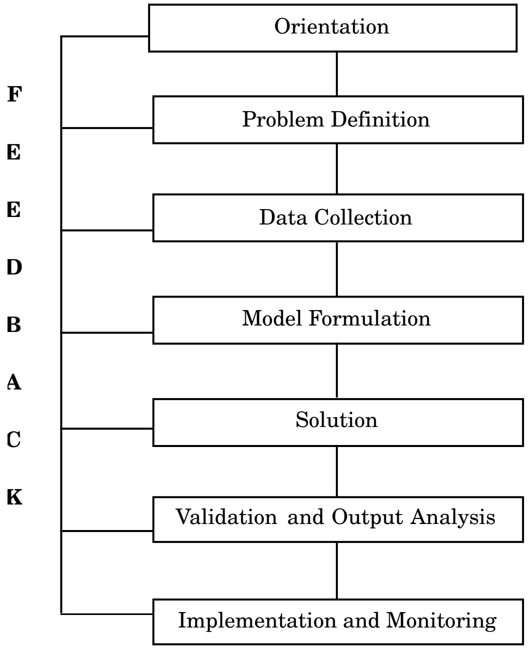

FIGURE 11.2.1 The operations research approach.

Each of these steps is now discussed in further detail. To illustrate how the steps might be applied, consider a typical scenario where a manufacturing company is planning production for the upcoming month. The company makes use of numerous resources (such as labor, production machinery, raw materials, capital, data processing, storage space, and material-handling equipment) to make a number of different products that compete for these resources. The products have differing profit margins and require different amounts of each resource. Many of the resources are limited in their availability. Additionally, there are other complicating factors such as uncertainty in the demand for the products, random machine breakdowns, and union agreements that restrict how the labor force can be used. Given this complex operating environment, the overall objective is to plan next month's production so that the company can realize the maximum profit possible while simultaneously finishing in a good position for the following month(s).

As an illustration of how one might conduct an operations research study to address this situation, consider a highly simplified instance of a production planning problem where there are two main product lines (widgets and gizmos, say) and three major limiting resources (A, B, and C) for which each of the products compete. Each product requires varying amounts of each of the resources and the company incurs different costs (labor, raw materials etc.) in making the products and realizes different revenues when they are sold. The objective of the OR project is to allocate the resources to the two products in an optimal fashion.

Orientation

The first step in the OR approach is referred to as problem orientation. The primary objective of this step is to constitute the team that will address the problem at hand and ensure that its members have a clear picture of the relevant issues. It is worth noting that a distinguishing characteristic of any OR study is that it is done by a multifunctional team. To digress slightly, it is also interesting that in recent years a great deal has been written and said about the benefits of project teams and that almost any industrial project today is conducted by multifunctional teams. Even in engineering education, teamwork has become an essential ingredient of the material that is taught to students and almost all academic engineering programs require team projects of their students. The team approach of OR is thus a very natural and desirable phenomenon.

Typically, the team will have a leader and be constituted of members from various functional areas or departments that will be affected by or have an effect on the problem at hand. In the orientation phase, the team typically meets several times to discuss all of the issues involved and to arrive at a focus on the critical ones. This phase also involves a study of documents and literature relevant to the problem to determine if others have encountered the same (or similar) problem in the past, and if so, to determine and evaluate what was done to address the problem. This is a point that often tends to be ignored, but to achieve a timely solution it is critical that one does not reinvent the wheel. In many OR studies, one actually adapts a solution procedure that has already been tried and tested, as opposed to developing a completely new one. The aim of the orientation phase is to obtain a clear understanding of the problem and its relationship to different operational aspects of the system, and to arrive at a consensus on what should be the primary focus of the project. In addition, the team should also have an appreciation for what (if anything) has been done elsewhere to solve the same (or similar) problem.

In our hypothetical production planning example, the project team might comprise members from engineering (to provide information about the process and technology used for production), production planning (to provide information on machining times, labor, inventory, and other resources), sales and marketing (to provide input on demand for the products), accounting (to provide information on costs and revenues), and information systems (to provide computerized data). Of course, industrial engineers work in all of these areas. In addition, the team might also have shop floor personnel such as a foreman or a shift supervisor and would probably be led by a midlevel manager who has relationships with several of the functional areas listed. At the end of the orientation phase, the team might decide that its specific objective is to maximize profits from its two products over the next month. It may also specify additional things that are desirable, such as some minimum inventory levels for the two products at the beginning of the next month, stable workforce levels, or some desired level of machine utilization.

Problem Definition

This is the second and, in a significant number of cases, the most difficult step of the OR process. The objective here is to further refine the deliberations from the orientation phase to the point where there is a clear definition of the problem in terms of its scope and the results desired. This phase should not be confused with the previous one since it is much more focused and goal oriented; however, a clear orientation aids immeasurably in obtaining this focus. Most practicing industrial engineers can relate to this distinction and the difficulty in moving from general goals such as increasing productivity or reducing quality problems to more specific, well-defined objectives that will aid in meeting these goals.

A clear definition of the problem contains three broad components. The first is the statement of an unambiguous objective. Along with a specification of the objective, it is also important to define its scope, that is, to establish limits for the analysis to follow. While a complete system level solution is always desirable, this may often be unrealistic when the system is very large or complex, and in many cases one must then focus on a portion of the system that can be effectively isolated and analyzed. In such instances it is important to remember that the scope of the solutions derived will also be bounded. Some examples of appropriate objectives might be (1) to maximize profits over the next quarter from the sales of our products, (2) to minimize the average downtime at work center X, (3) to minimize total production costs at Plant Y, or (4) to minimize the average number of late shipments per month to customers.

The second component of problem definition is a specification of factors that will affect the objective. These must further be classified into alternative courses of action that are under the control of the decision maker and uncontrollable factors over which he or she has no control. For example, in a production environment, the planned production rates can be controlled, but the actual market demand may be unpredictable (although it may be possible to scientifically forecast these with reasonable accuracy). The idea here is to form a comprehensive list of all the alternative actions that can be taken by the decision maker and that will then have an effect on the stated objective. Eventually, the OR approach will search for the particular course of action that optimizes the objective.

The third and final component of problem definition is a specification of the constraints on the courses of action—setting boundaries for the specific actions that the decision maker may take. As an example, in a production environment the availability of resources may set limits on what levels of production can be achieved. This is one activity where the multifunctional team focus of OR is extremely useful since constraints generated by one functional area are often not obvious to people in others. In general, it is a good idea to start with a long list of all possible constraints and then narrow this down to the ones that clearly have an effect on the courses of action that can be selected. The aim is to be comprehensive yet parsimonious when specifying constraints.

Continuing with our hypothetical illustration, the objective might be to maximize profits from the sales of the two products. The alternative courses of action would be the quantities of each product to produce next month, and the alternatives might be constrained by the fact that the amounts of each of the three resources required to meet the planned production must not exceed the expected availability of these resources. An assumption that might be made here is that all of the units produced can be sold. Note that at this point the entire problem is stated in words; later the OR approach will translate this into an analytical *model.*

Data Collection

In the third phase of the OR process, data is collected with the objective of translating the problem defined in the second phase into a model that can then be objectively analyzed. Data typically comes from two sources: observation and standards. The first corresponds to the case where data is actually collected by observing the system in operation, and typically, this data tends to derive from the technology of the system. For instance, operation times might be obtained by time studies or work methods analysis, resource usage or scrap rates might be obtained by making sample measurements over some suitable interval of time, and data on demands and availability might come from sales records, purchase orders, and inventory databases. Other data are obtained by using standards; a lot of cost-related information tends to fall into this category. Most companies have standard values for cost items such as hourly wage rates, inventory holding charges, selling prices, and so on; these standards must then be consolidated appropriately to compute costs of various activities. On occasion, data may also be solicited expressly for the problem at hand through the use of surveys, questionnaires, or other psychometric instruments.

One of the major driving forces behind the growth of OR has been the rapid growth in computer technology and the concurrent growth in information systems and automated data storage and retrieval. This has been a great boon because OR analysts now have ready access to data that was previously hard to obtain. Simultaneously, this has also made things difficult

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because many companies find themselves in the situation of being data-rich but information-poor. In other words, even though the data is all present somewhere and in some form, extracting useful information from these sources is often very difficult. This is one of the reasons why information systems specialists are invaluable to teams involved in any nontrivial OR project. Data collection can have an important effect on the previous step of problem definition, as well as on the following step of model formulation.

To relate data collection to our hypothetical production example, based on variable costs of production and the selling price of each of the products, it might be determined that the profit from selling one gizmo is $10 and one widget is $9. It might be determined based on time and work measurements that each gizmo and each widget respectively requires $\frac{7}{10}$ unit and 1 unit of resource 1, 1 unit and ⅔ unit of resource 2, and ⅒ unit and ¼ unit of resource 3. Finally, based on prior commitments and historical data on resource availability, it might be determined that in the next month there will be 630 units of resource 1708 units of resource 2, and 135 units of resource 3 available for use in producing the two products.

It should be emphasized that this is only a highly simplified illustrative example and the numbers here as well as the suggested data collection methods are also vastly simplified. In practice, these types of numbers can often be very difficult to obtain exactly, and the final values are typically based on extensive analyses of the system and represent compromises that are agreeable to everyone on the project team. As an example, a marketing manager might cite historical production data or data from similar environments and tend to estimate resource availability in very optimistic terms. On the other hand, a production planner might cite scrap rates or machine downtimes and develop a much more conservative estimate of the same. The final estimate would probably represent a compromise between the two that is acceptable to most team members.

Model Formulation

This is the fourth phase of the OR process. It is also a phase that deserves a lot of attention since modeling is a defining characteristic of all operations research projects. The term *model* is misunderstood by many and is therefore explained in some detail here. A model may be defined formally as a selective abstraction of reality. This definition implies that modeling is the process of capturing selected characteristics of a system or a process and then combining these into an abstract representation of the original. The main idea here is that it is usually far easier to analyze a simplified model than it is to analyze the original system, and as long as the model is a reasonably accurate representation, conclusions drawn from such an analysis may be validly extrapolated back to the original system.

There is no single correct way to build a model, and model building is more an art than a science. The key point to remember is that most often there is a natural trade-off between the accuracy of a model and its tractability. At the one extreme, it may be possible to build a very comprehensive, detailed, and exact model of the current system; this has the desirable feature of being a highly realistic representation of the original system. While the very process of constructing such a detailed model can often aid immeasurably in better understanding the system, the model may well be useless from an analytical perspective since its construction may be extremely time-consuming and its complexity precludes any meaningful analysis. At the other extreme, one could build a less comprehensive model with a lot of simplifying assumptions so that it can be analyzed easily. However, the danger here is that the model may be so lacking in accuracy that extrapolating results from the analysis back to the original system could cause serious errors. Clearly, one must draw a line somewhere in the middle where the model is a sufficiently accurate representation of the original system, yet remains tractable. Knowing where to draw such a line is precisely what determines a good modeler, and this is something that can come only with experience. In the formal definition of a model given previously, the key word is *selective.* Having a clear problem definition allows one to better determine the crucial aspects of a system that must be selected for representation by the model, and the ultimate intent is to arrive at a model that captures all the key elements of the system while remaining simple enough to analyze. Models may be broadly classified into the four categories that are discussed in the following sections.

Physical Models. These are actual, scaled-down versions of the original. Examples include a globe, a scale-model car, or a model of a flow line made with elements from a toy construction set. In general, such models are not very common in operations research, mainly because getting accurate representations of complex systems through physical models is often impossible.

Analogic Models. These are models that are a step down from the first category in that they are also physical models, but use a physical analog to describe the system, as opposed to an exact scaled-down version. Perhaps the most famous example of an analogic model was the anti-automatic-computation (ANTIAC) model, which demonstrated that one could conduct a valid operations research analysis without even resorting to the use of a computer. In this problem the objective was to find the best way to distribute supplies at a military depot to various demand points. Such a problem can be solved efficiently by using techniques from network flow analysis. However, the actual procedure that was used took a different approach. An anthill on a raised platform was chosen as an analog for the depot and little mounds of sugar on their own platforms were chosen to represent each demand point. The network of roads connecting the various nodes was constructed using bits of string with the length of each being proportional to the actual distance and the width to the capacity along that link. An army of ants was then released at the anthill and the paths that they chose to get to the mounds of sugar were then observed. After the model attained a steady state, it was found that the ants by virtue of their own tendencies had found the most efficient paths to their destinations! One could even conduct some postoptimality analysis. For instance, various transportation capacities along each link could be analyzed by proportionately varying the width of the link, and a scenario where certain roads were unusable could be analyzed by simply removing the corresponding links to see what the ants would then do. This illustrates an analogic model. More important, it also illustrates that while OR is typically identified with mathematical analysis, the use of an innovative model and problem-solving procedure such as the one just described is an entirely legitimate way to conduct an OR study.

Computer Simulation Models. With the growth in computational power, these models have become extremely popular over the last 10 to 15 years. A simulation model is one where the system is abstracted into a computer program. While the specific computer language used is not a defining characteristic, a number of languages and software systems have been developed solely for the purpose of building computer simulation models; a survey of the most popular systems may be found in *OR/MS Today* (February 1999, pp. 42–51). Typically, such software has syntax as well as built-in constructs that allow for easy model development. Very often they also have provisions for graphics and animation that can help one visualize the system being simulated. Simulation models are analyzed by running the software over some length of time that represents a suitable period when the original system is operating under steady state. The inputs to such models are the decision variables that are under the control of the decision maker. These are treated as parameters and the simulation is run for various combinations of values for these parameters. At the end of a run, statistics are gathered on various measures of performance and these are then analyzed using standard techniques. The decision maker then selects the combination of values for the decision variables that yields the most desirable performance.

Simulation models are extremely powerful and have one highly desirable feature: they can be used to model very complex systems without the need to make too many simplifying assumptions and without the need to sacrifice detail. On the other hand, one has to be very careful with simulation models because it is also easy to misuse simulation. First, before using the model it must be properly validated. While validation is necessary with any model, it is especially important with simulation. Second, the analyst must be familiar with how to use a simulation model correctly, including factors such as replication, run length, warm-up, and so forth. A detailed explanation of these concepts is beyond the scope of this chapter but the interested reader should refer to a good text on simulation. Third, the analyst must be familiar with various statistical techniques to analyze simulation output in a meaningful fashion. Fourth, constructing a complex simulation model on a computer can often be a challenging and relatively time-consuming task, although simulation software has developed to the point where this is becoming easier by the day. The reason these issues are emphasized here is that a modern simulation model can be very flashy and attractive, but its real value lies in its ability to yield insights into very complex problems. However, to obtain such insights, a considerable level of technical skill is required.

A final point to consider with simulation is that it does not provide one with an indication of the optimal strategy. In some sense it is a trial and error process since one experiments with various strategies that seem to make sense and looks at the objective results that the simulation model provides in order to evaluate the merits of each strategy. If the number of decision variables is very large, then one must necessarily limit oneself to some subset of these to analyze, and it is possible that the final strategy selected may not be the optimal one. However, from a practitioner's perspective, the objective often is to find a *good* strategy and not necessarily *the best* one, and simulation models are very useful in providing a decision maker with good solutions.

Mathematical Models. This is the final category of models and the one that traditionally has been most commonly identified with OR. In this type of model one captures the characteristics of a system or process through a set of mathematical relationships. Mathematical models can be deterministic or probabilistic. In the former type, all parameters used to describe the model are assumed to be known (or estimated with a high degree of certainty). With probabilistic models, the exact values for some of the parameters may be unknown, but it is assumed that they are capable of being characterized in some systematic fashion (e.g., through the use of a probability distribution). As an illustration, the critical path method (CPM) and the program evaluation and review technique (PERT) are two very similar OR techniques used in the area of project planning. However, CPM is based on a deterministic mathematical model that assumes that the duration of each project activity is a known constant, while PERT is based on a probabilistic model that assumes that each activity duration is random but follows some specific probability distribution (typically, the beta distribution). Very broadly speaking, deterministic models tend to be somewhat easier to analyze than probabilistic ones; however, this is not universally true.

Most mathematical models tend to be characterized by three main elements: decision variables, constraints, and objective function(s). *Decision variables* are used to model specific actions that are under the control of the decision maker. An analysis of the model will seek specific values for these variables that are desirable from one or more perspectives. Very often—especially in large models—it is also common to define additional convenience variables for the purpose of simplifying the model or for making it clearer. Strictly speaking, such variables are not under the control of the decision maker, but they are also referred to as decision variables. *Constraints* are used to set limits on the range of values that each decision variable can take on, and each constraint is typically a translation of some specific restriction (e.g., the availability of some resource) or requirement (e.g., the need to meet contracted demand). Clearly, constraints dictate the values that can be feasibly assigned to the decision variables—the specific decisions on the system or process that can be taken. The third and final component of a mathematical model is the *objective function.* This is a mathematical statement of some measure of performance (such as cost, profit, time, revenue, utilization, etc.) and is expressed as a function of the decision variables for the model. It is usually desired either to maximize or to minimize the value of the objective function, depending on what it represents. Very often, one may simultaneously have more than one objective function to optimize (e.g., maximize profits *and* minimize changes in workforce levels). In such cases there are two options. First, one could focus on a single objective and relegate the others to a secondary status by moving them to the set of constraints and specifying some minimum or maximum desirable value for them. This tends to be the simpler option and the one most commonly adopted. The other option is to use a technique designed specifically for multiple objectives (such as goal programming).

In using a mathematical model the idea is to first capture all the crucial aspects of the system using the three elements just described, and to then optimize the objective function by choosing (from among all values for the decision variables that do not violate any of the constraints specified) the specific values that also yield the most desirable (maximum or minimum) value for the objective function. This process is often called *mathematical programming.* Although many mathematical models tend to follow this form, it is certainly not a requirement; for example, a model may be constructed to simply define relationships between several variables and the decision maker may use these to study how one or more variables are affected by changes in the values of others. Decision trees, Markov chains, and many queuing models could fall into this category.

Before concluding this section on model formulation, we return to our hypothetical example and translate the statements made in the problem definition stage into a mathematical model by using the information collected in the data collection phase. To do this we define two decision variables G and W to represent respectively the number of gizmos and widgets to be made and sold next month. Then the objective is to maximize total profits given by $10G + 9W$. There is a constraint corresponding to each of the three limited resources, which should ensure that the production of gizmos and widgets does not use up more of the corresponding resource than is available for use. Thus for resource 1, this would be translated into the following mathematical statement: $0.7G + 1.0W \leq 630$, where the left-hand side of the inequality represents the resource usage and the right-hand side the resource availability. Additionally, we must also ensure that each G and W value considered is a nonnegative integer, since any other value is meaningless in terms of our definition of G and W. The completely mathematical model is

Maximize $\{\text{Profit} = 10G + 9W\}$, subject to

- $0.7G + 1.0W \leq 630$
- $1.0G + (2/3)W \leq 708$
- $0.1G + 0.25W \leq 135$
- $G, W \geq 0$ and integers

This mathematical program tries to maximize the profit as a function of the production quantities (G and W), while ensuring that these quantities are such that the corresponding production is feasible with the resources available.

Solution

The fifth phase of the OR process is the solution of the problem represented by the model. This is the area on which a huge amount of research and development in OR has been focused, and there is a plethora of methods for analyzing a wide range of models. It is impossible to get into details of these various techniques in a single introductory chapter such as this; however, an overview of some of the more important methods can be found elsewhere in this handbook. Generally speaking, some formal training in operations research is necessary in order to appreciate how many of these methods work and the interested reader is urged to peruse an introductory text on OR, including those listed at the end of this chapter. It is also worth mentioning that in recent years a number of software systems have emerged that (at least in theory) are black boxes for solving various models. However, some formal education in OR methods is still required (or at least strongly recommended) before using such systems.

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From the perspective of the practitioner, the most important thing is to be able to recognize which of the many available techniques is appropriate for the model constructed. The techniques themselves fall into several categories.

At the lowest level one might be able to use simple graphical techniques or even trial and error. However, even though the development of spreadsheets has made this much easier to do, it is usually an infeasible approach for most nontrivial problems. Most OR techniques are analytical in nature, and fall into one of four broad categories. First, there are simulation techniques, which are used to analyze simulation models. A significant part of these are the actual computer programs that run the model and the methods used to do so correctly. However, the more interesting and challenging part involves the techniques used to analyze the large volumes of output from the programs; typically, these encompass a number of statistical techniques. The interested reader should refer to a good book on simulation to see how these two parts fit together. The second category comprises techniques of mathematical analysis used to address a model that does not necessarily have a clear objective function or constraints but is nevertheless a mathematical representation of the system in question. Examples include common statistical techniques such as regression analysis, statistical inference, and analysis of variance, as well as others such as queuing, Markov chains, and decision analysis. The third category consists of optimum-seeking techniques, which are typically used to solve the mathematical programs described in the previous section in order to find the optimum (best) values for the decision variables. Specific techniques include linear, nonlinear, dynamic, integer, goal, and stochastic programming, as well as various network-based methods. A detailed exposition of these is beyond the scope of this chapter, but there are a number of excellent texts in mathematical programming that describe many of these methods. The final category of techniques is often referred to as *heuristics.* The distinguishing feature of a heuristic technique is that it is one that does not guarantee that *the best* solution will be found, but at the same time is not as complex as an optimum-seeking technique. Although heuristics could be simple, commonsense, rule-of-thumb type techniques, they are typically methods that exploit specific problem features to obtain good results. A relatively recent development in this area are so-called metaheuristics (such as genetic algorithms, tabu search, evolutionary programming, and simulated annealing), which are general-purpose methods that can be applied to a number of different problems. These methods in particular are increasing in popularity because of their relative simplicity and because increases in computing power have greatly increased their effectiveness.

In applying a specific technique something that is important to keep in mind from a practitioner's perspective is that it is often sufficient to obtain a good solution even if it is not guaranteed to be the best solution. If neither resource availability nor time were an issue, one would of course look for the optimum solution. However, this is rarely the case in practice, and timeliness is of the essence in many instances. In this context, it is often more important to quickly obtain a solution that is satisfactory as opposed to expending a lot of effort to determine the optimum one, especially when the marginal gain from doing so is small. The economist Herbert Simon uses the term *satisficing* to describe this concept—one searches for the optimum but stops along the way when an acceptably good solution has been found.

At this point, some words about computational aspects are in order. When applied to a nontrivial, real-world problem, almost all of the techniques discussed in this section require the use of a computer. Indeed, the single biggest impetus for the increased use of OR methods has been the rapid increase in computational power. Although there are still large-scale problems whose solutions require the use of mainframe computers or powerful workstations, many big problems today are capable of being solved on desktop microcomputer systems. There are many computer packages (and their number is growing daily) that have become popular because they are easy to use and are typically available in various versions or sizes and interface seamlessly with other software systems; depending on their specific needs end users can select an appropriate configuration. Many of the software vendors also offer training and consulting services to help users get the most out of their systems. Some specific techniques for which commercial software implementations are available today include optimization/mathematical programming (including linear, nonlinear, integer, dynamic, and goal programming), network flows, simulation, statistical analysis, queuing, forecasting, neural networks, decision analysis, and PERT/CPM. Also available today are commercial software systems that incorporate various OR techniques to address specific application areas including transportation and logistics, production planning, inventory control, scheduling, location analysis, forecasting, and supply chain management. Some examples of popular OR software systems include CPLEX, LINDO, OSL, MPL, SAS, and ARENA, to name just a few. While it would clearly be impossible to describe herein the features of all available software, magazines such as *OR/MS Today* and *IE Solutions* regularly publish separate surveys of various categories of software systems and packages. These publications also provide pointers to different types of software available; as an example, the December 1999 issue of *OR/MS Today* (pp. 69–72) provides a complete resource directory for software and consultants. Updates to such directories are provided periodically. The ability to solve complex models/problems is much easier today than it was a decade or two ago, and there are plenty of readily available resources.

We conclude this section by examining the solution to the model constructed earlier for our hypothetical production problem. Using linear programming to solve this model yields the optimal solution of $G = 540$ and $W = 252$—the production plan that maximizes profits for the given data calls for the production of 540 gizmos and 252 widgets. The optimal solution yields a profit of \$7668 and uses up all of the first two resources while leaving 18 units of the last resource unused. Note that this solution is not apparent by just looking at the mathematical model: if one were greedy and tried to make as many gizmos as possible (since they yield higher profits per unit than the widgets), this would yield $G = 708$ and $W = 0$ (at which point all of the second resource is used up). However, the resulting profit of \$7080 is about 8 percent less than the one obtained via the optimal plan. The reason, of course, is that this plan does not make the most effective use of the available resources and fails to take into account the interaction between profits and resource utilization. While the actual difference is small for this hypothetical example, the benefits of using a good OR technique can result in very significant improvements for large real-world problems.

Validation and Analysis

Once a solution has been obtained two things need to be done before one even considers developing a final policy or course of action for implementation. The first is to verify that the solution itself makes sense. Oftentimes, this is not the case, and the most common reason is that the model used was not accurate or did not capture some major issue. The process of ensuring that the model is an accurate representation of the system is called validation and this is something that (whenever possible) should be done before actual solution. However, it is sometimes necessary to solve the model to discover inaccuracies in it. A typical error that might be discovered at this stage is that some important constraint was ignored in the model formulation; this will lead to a solution that is clearly recognized as being infeasible and the analyst must then go back and modify the model and re-solve it. This cycle continues until one is sure that the results are sensible and come from a valid system representation.

The second part of this step in the OR process is referred to as postoptimality analysis, or in layperson's terms, a *what-if* analysis. Recall that the model that forms the basis for the solution obtained is (1) a selective abstraction of the original system, and (2) constructed using data that in many cases is not 100 percent accurate. Since the validity of the solution obtained is bounded by the model's accuracy, a natural question that is of interest to an analyst is: "How robust is the solution with respect to deviations in the assumptions inherent in the model and in the values of the parameters used to construct it?" To illustrate this with our hypothetical production problem, examples of some questions that an analyst might wish to ask are (1) "Will the optimum production plan change if the profits associated with widgets were overestimated by 5 percent, and if so how?" or (2) "If some additional amount of resource 2 could be purchased at a premium, would it be worth buying and if so, how much?" or (3) "If machine unreliability were to reduce the availability of resource 3 by 8 percent, what effect would this have on the optimal policy?" Such questions are especially of interest to managers and decision makers who live in an uncertain world, and one of the most important aspects of a good OR project is the ability to provide not just a recommended course of action but also details on its range of applicability and its sensitivity to model parameters.

Before ending this section it is worth emphasizing that similar to a traditional industrial engineering project, the result of an OR project is not a definitive solution to a problem. Rather, it is an objective answer to the questions posed by the problem and one that puts the decision maker in the correct ballpark. As such, it is critical to temper the analytical solution obtained with common sense and subjective reasoning before finalizing a plan for implementation. From a practitioner's standpoint, a sound, sensible and workable plan is far more desirable than incremental improvements in the quality of the solution obtained. This is the emphasis of this penultimate phase of the OR process.

Implementation and Monitoring

The last step in the OR process is to implement the final recommendation and establish control over it. Implementation entails the construction of a team whose leadership will consist of some of the members on the original OR team. This team is typically responsible for the development of operating procedures or manuals and a timetable for putting the plan into effect. Once implementation is complete, responsibility for monitoring the system is usually turned over to an operating team. From an OR perspective, the primary responsibility of the latter is to recognize that the implemented results are valid only as long as the operating environment is unchanged and the assumptions made by the study remain valid. Thus, when there are radical departures from the bases used to develop the plan, one must reconsider one's strategy. As a simple example with our production problem, if a sudden strike by the workforce causes a drastic reduction in the availability of labor (perhaps resource 1), one must reconsider the plan completely to derive an alternative course of action. As a final word on implementation, it should be emphasized that a major responsibility of the operations research analyst is to convey the results of the project to management in an effective fashion. This is something that is unfortunately not emphasized sufficiently, and there are many instances of a successful study not being implemented because the details and the benefits are not conveyed effectively to management. While this is of course true of any project, it is especially significant with OR because of its mathematical content and its potential to not be fully understood by a manager without a strong quantitative background.

OR IN THE REAL WORLD

In this section some examples of successful real-world applications of operations research are provided. These should give the reader an appreciation for the diverse kinds of problems that OR can address, as well as for the magnitude of the savings that are possible. Without any doubt, the best source for case studies and details of successful applications is the journal *Interfaces,* which is a publication of the Institute for Operations Research and the Management Sciences (INFORMS). This journal is oriented toward the practitioner and much of the exposition is in laypersons' terms; at some point, every practicing industrial engineer should refer to this journal to appreciate the contributions that OR can make. All of the applications that follow have been extracted from recent issues of *Interfaces.*

Before describing these applications, it is important to briefly discuss how operations research is perceived in the real world. An unfortunate reality is that OR has received more than its fair share of negative publicity. It has sometimes been viewed as an esoteric science with little relevance to the real world, and some critics have even referred to it as a collection

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of techniques in search of a problem to solve! Clearly, this criticism is untrue, and there is plenty of documented evidence that when applied properly, and with a problem-driven focus, OR can result in benefits that can be quite spectacular.

Nevertheless, there is also evidence to suggest that (unfortunately) the criticisms leveled against OR are not completely unfounded. This is because OR is often not applied as it should be: People have often taken the myopic view that OR is a specific *method* as opposed to a complete and systematic *process.* In particular, there has been an inordinate amount of emphasis on the modeling and solution steps, possibly because these clearly offer the most intellectual challenge. However, it is critical to maintain a problem-driven focus; the ultimate aim of an OR study is to *implement a solution* to the problem being analyzed. Building complex models that are ultimately intractable, or developing highly efficient solution procedures to models that have little relevance to the real world may be fine as intellectual exercises but run contrary to the practical nature of operations research. Unfortunately, this fact has sometimes been forgotten. Another valid criticism is that many analysts are notoriously poor at communicating the results of an OR project in terms that can be understood and appreciated by practitioners who may not necessarily have a great deal of mathematical sophistication or formal training in OR. The bottom line is that an OR project can be successful only if sufficient attention is paid to each of the seven steps of the process and the results are communicated to the end users in an understandable form.

Production Planning at Harris Corporation—Semiconductor Section

For our first application, we look at an area that is readily appreciated by every industrial engineer: production planning and due date quotation [1]. The semiconductor section of Harris Corporation was for a number of years a fairly small business catering to a niche market in the aerospace and defense industries where the competition was minimal. However, in 1988 a strategic decision was made to acquire General Electric's semiconductor product lines and manufacturing facilities. This immediately increased the size of Harris's semiconductor operations and product lines by roughly three times, and more important, catapulted Harris into commercial market areas such as automobiles and telecommunications where the competition was stiff. Given the new diversity of product lines and the tremendous increase in the complexity of production planning, Harris was having a hard time meeting delivery schedules and staying competitive financially—clearly, a better system was required.

In the orientation phase it was determined that the material requirements planning (MRP) type systems used by a number of its competitors would not be a satisfactory answer, and a decision was made to develop a planning system that would meet Harris's unique needs. The result was IMPReSS, an automated production planning and delivery quotation system for the entire production network. The system is an impressive combination of heuristics as well as optimization-based techniques. It works by breaking up the overall problem into smaller, more manageable problems by using a heuristic decomposition approach. Mathematical models within the problem are solved using linear programming along with concepts from material requirements planning. The entire system interfaces with sophisticated databases allowing for forecasting, quotation and order entry, materials, and dynamic information on capacities. Harris estimates that this system has increased on-time deliveries from 75 to 95 percent with no increase in inventories, helped the company move from $75 million in losses to $40 million in profits annually, and allowed it to plan its capital investments more efficiently.

Gasoline Blending at Texaco

For another application to production planning, but this time in a continuous as opposed to discrete production environment, we look at a system in use at Texaco [2]. One of the major applications of OR is in the area of gasoline blending at petroleum refineries, and virtually all

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major oil companies use sophisticated optimization models in this area. At Texaco the system is called StarBlend and runs on networked microcomputers. As some background, the distillation of crude petroleum produces a number of different products at different distillation temperatures. Each of these may be further refined through cracking (where complex hydrocarbons are broken into simpler ones) and recombination. These various output streams are then blended together to form end products such as different grades of gasoline (leaded, unleaded, super unleaded, etc.), jet fuel, diesel fuel, and heating oil. The planning problem is very complex, because different grades of crude yield different concentrations of output streams and incur different costs, and different end products garner different revenues and use different amounts of refinery resources. Considering just one product—gasoline—there are various properties that constrain the blends produced. These include the octane number, lead and sulfur content, volatilities, and Reid vapor pressure, to name a few. Regulatory constraints impose certain restrictions as well.

As an initial response to this complex problem, in the early to mid-1980s Texaco developed a system called OMEGA. At the heart of this was a nonlinear optimization model that supported an interactive decision support system for optimally blending gasoline; this system alone was estimated to have saved Texaco about $30 million annually. StarBlend is an extension of OMEGA to a multiperiod planning environment where optimal decisions could be made over a longer planning horizon as opposed to a single period. In addition to blend quality constraints, the optimization model also incorporates inventory and material balance constraints for each period in the planning horizon. The optimizer uses an algebraic modeling language called GAMS and a nonlinear solver called MINOS, along with a relational database system for managing data. The whole system resides within a user-friendly interface, and in addition to immediate blend planning, it can also be used to analyze various what-if scenarios for the future and for long-term planning.

FMS Scheduling at Caterpillar

For our third application we look at the use of a simulation model. This model was applied to derive schedules for a flexible manufacturing system (FMS) at Caterpillar, Inc. [3]. (The interested reader may refer to any text on computer-integrated manufacturing for details about FMSs.) Typically, FMSs are systems of general-purpose computer numerical control (CNC) machines linked together by an automated material-handling system and completely controlled by computers. The FMS used at Caterpillar had seven CNC milling machines, a fixturing station, and a tool station, with material and tool handling being performed by four automated guided vehicles (AGVs) traveling along a one-way guided wire path. FMSs can provide tremendous increases in capacity and productivity because of the high levels of automation inherent in them and their potential to manufacture a wide variety of parts. However, this comes with a price: These systems are also very complex and the process of planning and scheduling production on an FMS and then controlling its operation can be a difficult one. The efficiency of the scheduling procedure used can have a profound effect on the magnitude of the benefits realized.

At Caterpillar, a preliminary analysis showed that the FMS was being underutilized and the objective of the project was to define a good production schedule that would improve utilization and free up more time to produce additional parts. In the orientation phase it was determined that the environment was much too complex to represent it accurately through a mathematical model, and therefore simulation was selected as an alternative modeling approach. It was also determined that minimizing the makespan (which is the time required to produce all daily requirements) would be the best objective since this would also maximize and balance machine utilization. A detailed simulation model was then constructed using a specialized language called SLAM. In addition to the process plans required to specify the actual machining of the various part types, this model also accounted for a number of factors such as material handling, tool handling, and fixturing. Several alternatives were then simulated to observe how the system would perform. It was determined that a fairly simple set of heuristic scheduling rules could yield near optimal schedules for which the machine utilizations were almost 85 percent. However, what was more interesting was that this study also showed that the stability of the schedule was strongly dependent on the efficiency with which the cutting tools used by the machines could be managed. In fact, as tool quality starts to deteriorate, the system starts to get more and more unstable and the schedule starts to fall behind due dates. To avoid this problem, the company had to suspend production over the weekends to replace worn-out tools, or occasionally used overtime to get back on schedule. The key point from this application is that a simulation model could be used to analyze a highly complex system for a number of what-if scenarios and to gain a better understanding of the dynamics of the system.

Fleet Assignment at Delta Airlines

One of the most challenging, as well as rewarding, application areas of OR has been the airline industry. We briefly describe one such application at Delta Airlines [4]. The problem solved is often referred to as the fleet assignment problem. Delta flies over 2500 domestic flight legs each day and uses about 450 aircraft from 10 different fleets, and the objective was to assign aircraft to flight legs in such a way that revenues from seats are maximized. The trade-off is quite simple: if a plane is too small then the airline loses potential revenue from passengers who cannot be accommodated on board, and if it is too large, then the unoccupied seats represent lost revenue (in addition to the larger aircraft being more expensive to operate). Thus, the objective is to ensure that an aircraft of the correct size be available when and where required. Unfortunately, ensuring that this can happen is tremendously complicated since there are a number of logistical issues that constrain the availability of aircraft at different times and locations.

The problem is modeled by a very large mixed-integer linear program—a typical formulation could result in about 60,000 variables and 40,000 constraints. The planning horizon for each problem is one day since the assumption is made that the same schedule is repeated each day (exceptions such as weekend schedules are handled separately). The primary objective of the problem is to minimize the sum of operating costs (including such things as crew and fuel costs and landing fees) and costs from lost passenger revenues. The bulk of the constraints are structural in nature and result from modeling the conservation of flow of aircraft from the different fleets to different locations around the system at different scheduled arrival and departure times. In addition, there are constraints governing the assignment of specific fleets to specific legs in the flight schedule. There are also constraints relating to the availability of aircraft in the different fleets, regulations governing crew assignments, scheduled maintenance requirements, and airport restrictions. It is clear that the task of gathering and maintaining the information required to mathematically specify all of these constraints is in itself a tremendous task. Although building such a model is difficult but not impossible, the ability to solve it to optimality was impossible until the very recent past. However, computational OR has developed to the point that it is now feasible to solve such complex models; the system at Delta is called Coldstart and uses highly sophisticated implementations of linear and integer programming solvers. The financial benefits from this project have been tremendous; for example, according to Delta the savings during the period from June 1 to August 31, 1993, were estimated at about $220,000 per day.

KeyCorp Service Excellence Management System

For our final application we turn to the service sector and an industry that employs many industrial engineers—banking. This application demonstrates how operations research was used to enhance productivity and quality of service at KeyCorp, a bank holding company headquartered in Cleveland, Ohio [5]. Faced with increasing competition from nontraditional sources and rapid consolidation within the banking industry, KeyCorp's aim was to provide a suite of world-class financial products and services instead of being a traditional bank. The key element in being able to do this effectively is high-quality customer service and a natural trade-off faced by a manager concerned staffing and service—better service in the form of shorter waiting times required additional staffing that came at a higher cost. The objective of the project was to provide managers with a complete decision support system, which was dubbed SEMS (Service Excellence Management System).

The first step was the development of a computerized system to capture data on performance. The system captured the beginning and ending time of all components of a teller transaction including host response time, network response time, teller controlled time, customer controlled time, and branch hardware time. The data gathered could then be analyzed to identify areas for improvement. Queuing theory was used to determine staffing needs for a prespecified level of service. This analysis yielded a required increase in staffing that was infeasible from a cost standpoint; therefore, an estimate was made of the reductions in processing times that would be required to meet the service objective with the maximum staffing levels that were feasible. Using the performance capture system, KeyCorp was then able to identify strategies for reducing various components of the service times. Some of these involved upgrades in technology while others focused on procedural enhancements, and the result was a 27 percent reduction in transaction processing time. Once the operating environment was stabilized, KeyCorp introduced the two major components of SEMS to help branch managers improve productivity. The first, a teller productivity system, provided the manager with summary statistics and reports to help with staffing, scheduling, and identifying tellers who required further training. The second, a customer wait time system, provided information on customer waiting times by branch, by time of day, and by half-hour intervals at each branch. This system used concepts from statistics and queuing theory to develop algorithms for generating the required information. Using SEMS, a branch manager could thus autonomously decide on strategies for further improving service. The system was gradually rolled out to all of KeyCorp's branches and the results were very impressive. For example, on average, customer processing times were reduced by 53 percent and customer wait times dropped significantly with only 4 percent of customers waiting more than 5 minutes. The resulting savings over a five-year period were estimated at $98 million.

SUMMARY

This chapter provides an overview of operations research, its origins, its approach to solving problems, and some examples of successful applications. From the standpoint of an industrial engineer, OR is a tool that can contribute a great deal to improve productivity. It should be emphasized that OR is neither esoteric nor impractical, and the interested IE is urged to study this topic further for its techniques as well as its applications—the potential rewards can be enormous.

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BIOGRAPHY

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CHAPTER 11.3

GUIDE TO OPTIMIZATION MODELS

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This chapter provides a summary of the most important optimization models, including linear, dynamic, integer, network, and nonlinear programming. Though the presentation emphasizes the practical aspects of optimization, it also provides a basic understanding of the theoretical foundation of the optimization.

A good part of this chapter is dedicated to linear programming because it forms an important foundation for other optimization models. Additionally, linear programming is the single most successful application tool among all operations models.

GENERAL DEFINITION OF OPTIMIZATION

Humans have always strived to do things efficiently. Throughout history, tools and implements were developed to perform tasks that were designed to complement human physical strength. The invention of the wheel is probably the most revolutionizing optimization tool developed by humans.

In today's complex business and industrial environments, the solution of operational problems cannot be achieved by technological advances alone. The multitude of options available for implementing an operational plan has mandated the development of systematic procedures for selecting the options that best benefit the organization as a whole. The optimization models of operations research are designed to solve such complex problems.

An optimization system may be regarded generally as a resource allocation problem in which limited resources are assigned to activities in a manner that will produce the best value for a selected measure of performance. Such a measure of performance may typically involve minimization of cost or maximization of profit. A simple example of an optimization system involves the determination of the level of production of a number of products that compete for limited raw materials, with the objective of maximizing the total profit for all products. In this situation, each product represents an activity whose optimal production level is determined from the solution of the model.

The general framework of an optimization model can be summarized as follows:

Maximize or minimize (an objective)

subject to

(system constraints)

Both the objective and the constraints are expressed as mathematical functions of the unknown variables. Suppose that a system has n activities that are represented by the variables $x_1, x_2, \dots, x_n$. The associated optimization model may then be written as follows:

$$\text{Maximize or minimize } f(x_1, x_2, \dots, x_n)$$

subject to

$$g_i(x_1, x_2, \dots, x_n) \le b_i, \quad i = 1, 2, \dots, m$$

$$x_1, x_2, \dots, x_n \ge 0$$

In this model, the function f represents the objective. The system is assumed to have m limited resources in which b_i is the maximum amount of resource i. The function g_i represents the amount of resource i used by all n activities. The nonnegativity constraints ($x_1, x_2, \dots, x_n \ge 0$) recognize the fact that in a typical resource allocation model, the activities cannot assume negative values.

EXAMPLE 11.3.1 *Suppose that a company produces leather jackets and handbags. A jacket requires 5 square meters of leather, and a handbag uses only 3 square meters. The labor requirements for a single jacket and a single handbag are 10 and 9 hours, respectively. The daily supply of leather is 150 square meters and the available labor time per day is 360 hours. The profit per jacket is \$80 and that of a handbag is \$50. What are the best daily production levels for the jackets and the bags?*

The construction of the model starts by defining the variables of the problem. Let

$$x_1 = \textit{Number of jackets produced per day}$$

$$x_2 = \textit{Number of bags produced per day}$$

Using these definitions, the objective is to maximize the total profit $z = 80x_1 + 50x_2$*. The constraints of the model represent the limits on two resources: leather and labor time. Given that the two products use* ($5x_1 + 3x_2$) *square meters of leather, the associated constraint is written as*

$$5x_1 + 3x_2 \le 150$$

In a similar manner, the labor constraint is written as

$$10x_1 + 9x_2 \le 360$$

The complete model may thus be summarized as follows:

$$\textit{Maximize } z = 80x_1 + 50x_2$$

subject to

$$5x_1 + 3x_2 \le 150$$

$$10x_1 + 9x_2 \le 360$$

$$x_1, x_2 \ge 0$$

The optimum solution of the model should determine the values of x_1 *and* x_2 *that maximize the total profit* z*. We will show in the section entitled "Linear Optimization Algorithms" that the number of feasible solutions,* x_1 *and* x_2*, that satisfy the given constraints is indeed infinite. For this reason, we need a systematic and computationally efficient procedure that will select the* *optimum solution from among these infinite possibilities. This result is accomplished by using the various optimization techniques that will be presented in the remainder of this chapter.*

WHAT IS IN THE NAME?

An operations researcher once said following the development of a new optimization technique, "When you have a new baby, you give it a name." And so it goes with the wide spectrum of names that currently characterize the field of operations research. In the first section ("General Definition of *Optimization*"), we used the functions $f(x_1, x_2, \ldots, x_n)$ and $g_i(x_1, x_2, \ldots, x_n)$ to define the objective and constraint functions generically. These mathematical functions may be linear (as in Example 11.3.1) or nonlinear, and the variables may be continuous or discrete, depending on the system being modeled. The complexity of the resulting mathematical models precludes the possibility of developing a general algorithm for solving all problems. Instead, different algorithms have been developed to account for special cases of the functions f and g_i. For example, if all the functions f and g_i are linear (as in Example 11.3.1), the resulting model is a linear program. If, additionally, the variables x_j are restricted to integer values, then the model is an integer linear program.

In the remainder of this chapter, we will present an exposition of operations research algorithms. The presentation comes under the four major solution categories: *linear, nonlinear, dynamic,* and *heuristic algorithms.* The principal thrust of the presentation is to familiarize you with the application and computational aspects of these algorithms.

The algorithmic developments in the field of operations research during the past 5 decades have been tremendous and extensive. Because of space limitations, it is impossible to provide a summary of *all* such algorithms. Instead, we will concentrate on the most prominent techniques in the field. The objective is to provide a panorama of the rich contributions in the field.

LINEAR OPTIMIZATION ALGORITHMS

Linear optimization deals with mathematical models in which all the functions are linear. Variations in the structure of the model and the characteristics of the variables give rise to a variety of solution algorithms. The most prominent of these algorithms will be presented in this section.

Linear Programming

Linear programming is the oldest and, certainly, the most prominent of all operations research techniques. Not only does the technique enjoy a wide range of applications in the private and public sectors, but it is also the most efficient computationally among all optimization techniques. Indeed, because of the proven computational efficiency of linear programming, a number of problems in the areas of integer and nonlinear programming are solved basically by using a sequence of linear programs.

We will start the discussion on linear programming by providing a graphical solution to a two-variable problem. This solution will provide a concrete picture of how the linear programming algorithm works.

EXAMPLE 11.3.2 *We consider the linear program in Example 11.3.1. Figure 11.3.1 graphs the feasible solution space that satisfies all the constraints of the problem. The solution space shows that the problem has infinity of feasible solutions. The optimum solution is the feasible solution that yields the largest value of the profit function z. The slope of the objective function shows that the optimum profit occurs at point C of the solution space. It calls for producing 18 jackets and 20 bags daily, with a resulting profit of $2440 per day.*

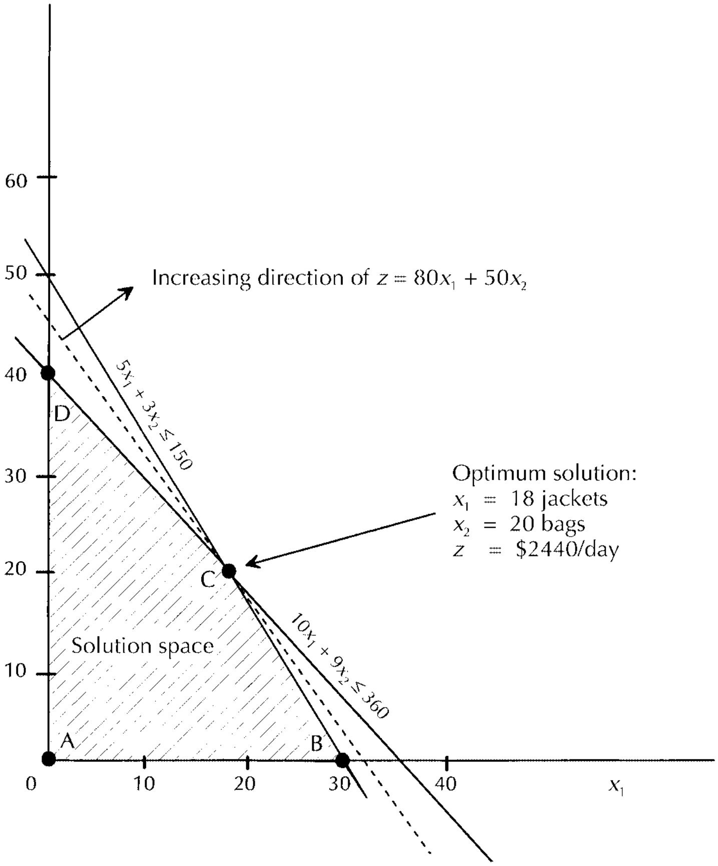

FIGURE 11.3.1 Feasible space and optimal solution for the linear program of Example 11.3.1.

The main result that we can deduce from the graphical solution in Fig. 11.3.1 is that, depending on the slope of the objective function, the optimum solution of the problem can always be associated with one of the *corner points* (also known as *extreme points*) of the solution space. In essence, this observation reduces the number of candidates for the optimal from an infinite number of points to a finite number of corner points. This result is the crux of the algebraic algorithm called the *simplex method.*

The simplex algorithm can solve any linear program regardless of the size of the problem. It usually starts at the origin and then (intelligently) selects an adjacent corner point that will improve the objective value z. By repeating the process, we eventually reach the optimum corner point.

The repetitive and voluminous nature of linear programming computations mandates the development of computationally efficient algorithms. Such algorithms include the *revised simplex,* the *dual simplex,* and the *primal-dual simplex.* Despite the different computational details, all of these algorithms are rooted in the fact that the optimum solution is associated with a corner point of the solution space.

The solution of a linear program by the simplex method offers a wealth of information that goes beyond the optimum value of the variables and their associated objective value. Indeed, the linear programming problem can be viewed as a *resource allocation* model in which the objective is to maximize profit subject to limited resources. This concept is further enhanced by defining the *dual problem* associated with each linear program.

The *dual problem* is constructed symmetrically from the original (also known as *primal*) model as follows:

- A dual variable is defined for each primal constraint.
- A dual constraint is constructed for each primal variable.
- If the primal objective is maximization, then the dual objective is minimization, and vice versa.

The rules for constructing the dual problem from the primal model can be found in Taha [2]. We use the model of Example 11.3.2 to illustrate this definition.

EXAMPLE 11.3.3 *The primal model is given in Example 11.3.2 as follows:*

$$\text{Maximize } z = 80x_1 + 50x_2$$

subject to

$$5x_1 + 3x_2 \leq 150$$

$$10x_1 + 9x_2 \leq 360$$

$$x_1, x_2 \geq 0$$

The corresponding dual problem is then constructed in the following manner:

$$\text{Minimize } w = 150y_1 + 360y_2$$

subject to

$$5y_1 + 10y_2 \geq 80$$

$$3y_1 + 9y_2 \geq 50$$

$$y_1, y_2 \geq 0$$

The optimal solution of the dual problem is given as follows:

$$y_1 = 14.667, \quad y_2 = .667, \quad w = 2440$$

The dual problem is more than just a mathematical definition. It provides "neat" economic interpretations when the primal is regarded as a resource allocation model. In particular, the mathematical theory of the primal/dual problems tells us that, at the optimum solution for both problems, we have the following result:

$$\text{Primal objective value} = \text{dual objective value}$$

This result is demonstrated in Examples 11.3.2 and 11.3.3 by the fact that at the optimum, $z = w = 2440$.

In the context of a resource allocation model, we may regard the objective function as representing profit (\$) and the right-hand sides of the different constraints as the limits on the availability of the limited resources. Thus, from the mathematical definition of the dual, the result given earlier may be interpreted as follows:

$$\$\text{ amount} = \textstyle\sum_i \text{ (amount of resource } i \times \text{dual variable } y_i)$$

This identity shows that the dual variable y_i can be interpreted as the *worth per unit of resource i.* Thus, in Example 11.3.2, given that at the optimum $y_1 = 14.67$ and $y_2 = .67$, we conclude that one additional square meter of leather contributes \$14.67 to profit, whereas one additional hour of labor contributes only \$.67. Thus, if we are asked to prioritize the degree of importance of the two resources, we would be inclined to increase the availability of the leather before we consider increasing labor time.

Interpretations similar to the preceding one provide economic information about the resource allocation model that can be useful to the decision maker. There are other results, also based on duality theory, that shed more light on interpreting the resource allocation problem when it is modeled as a linear program (see Taha [2]).

Actually, duality theory has made other contributions to advance the computational efficiency of special linear programming models. Two such models include the *assignment model,* in which it is desired to assign operators to machines in the least expensive way, and the *transportation model,* in which it is desired to determine the optimum shipping schedules between a number of sources (e.g., plants) and a number of destinations (e.g., retailers). Using duality, it is possible to develop efficient algorithms for these models.

The utility of linear programming is enhanced by the development of techniques that analyze the changes in the optimum solution when the parameters of the model are changed. These techniques include *sensitivity analysis,* in which discrete changes in the parameters take place, and *parametric programming,* in which the parameters are changed continuously according to predetermined functions. For example, we may be interested in studying the changes in the optimal solution that result from making changes in the availability of the resources and the objective function coefficients. Both sensitivity analysis and parametric programming provide information about the behavior of the optimum that otherwise cannot be gleaned directly from the solution of the linear program by the simplex method. In a sense, the techniques add a dynamic dimension to an otherwise static model by allowing us to study the impact on the optimum solution of making changes in the parameters of the model.

Though the simplex method has been used for decades as the most effective algorithm for solving linear programs, a new algorithm, called the *interior point method,* was introduced in 1984 as a viable alternative to the simplex algorithm. It differs in that the iterations do not follow the edges of the solution space as in the simplex method. Instead, the solution path cuts across the interior of the solution space. Apparently, the interior point algorithm has shown promising results in solving extremely large linear programs. However, it is not as widely used as the simplex method, perhaps because the software is not readily available to the average user. A software based on the interior point algorithm under the trademark KORBX has been developed by AT&T.

Network Programming

Our lives are dominated by networks and network flow. Most prominently, we deal daily with communication, transportation, and electrical power networks. In a modern society, speed and efficiency are dominant prerequisites for the operation of these networks. Though we do not expect to wait excessively when we call for emergency help, the cost of offering such services must be viable economically.

As the name reveals, network programming is dedicated to the design of *efficient* networks that offer *improved* service. Example 11.3.4 demonstrates a general application of networks.

EXAMPLE 11.3.4 *A company manufactures a basic chemical compound that is used by other manufacturers to produce paint products. The company owns two plants that are supplied with raw material from two suppliers. The contracts call for minimum deliveries of 500 and 750 tons daily from suppliers 1 and 2 at the respective prices of \$200 and \$210 per ton. It takes 1 ton of raw material to manufacture 1 ton of the basic chemical compound. The transportation costs from the suppliers to the plants are given in Table 11.3.1.*

TABLE 11.3.1 Transportation Costs from the Suppliers to the Plants

Supplier	Plant 1	Plant 2
1	\$10	\$12
2	\$9	\$13

The daily production capacities and the cost per ton at the two plants are summarized in Table 11.3.2.

TABLE 11.3.2 Daily Production Capacities and Cost per Ton at Two Plants

Plant	Production cost (\$/ton)	Minimum capacity (tons)	Maximum capacity (tons)
1	\$25	400	800
2	\$28	450	900

The daily demands at the two centers are 660 and 800 tons, respectively. The transportation cost per ton between the plants and the distribution centers are given in Table 11.3.3.

TABLE 11.3.3 Transportation Cost per Ton Between the Plants and the Distribution Centers

Plant	Center 1	Center 2
1	\$3	\$4
2	\$5	\$2

Figure 11.3.2 provides the network representing the problem. It consists of nodes and arcs. The nodes represent points of origin and destinations, and the arcs represent the amount of flow from one node to another. The unit flow cost is shown directly on each arc. The network includes the source node 1 that represents the origin of the raw material. Nodes 2 and 3 represent the two suppliers. The minimum capacity limits for the two suppliers, together with the associated delivery cost per ton, are shown on arcs (1, 2) and (1, 3), respectively. To introduce the plants' capacities, each plant is represented by two nodes, which may be viewed as the input and output points of the plant. Thus, plants 1 and 2 are represented by the respective pairs of nodes (4 and 6) and (5 and 7). The capacities of the two plants are shown on arcs (4, 6) and (5, 7) as (400, 800) and (450, 900), respectively. The output nodes (6 and 7) of the two plants are linked to the distribution centers repre-

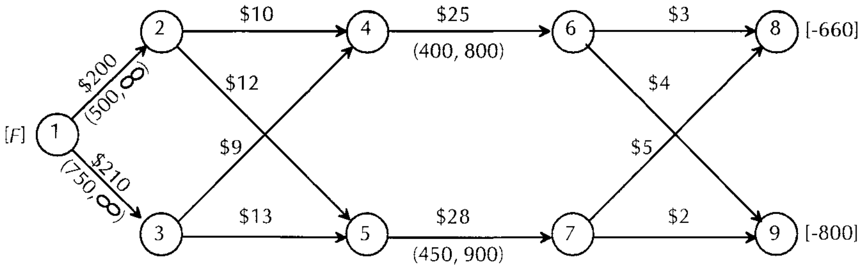

FIGURE 11.3.2 Network reproduction of the operation of the chemical company.

sented by nodes 8 and 9 using the transportation arcs (6, 8), (6, 9), (7, 8), and (7, 9). The final daily demands at distribution centers 8 and 9 are 660 and 800 tons, respectively.

The solution of the network model reduces to determining the optimum feasible flow in the arcs that will satisfy the arc capacity restrictions. The objective is to minimize the total cost of manufacturing and of transportation.

The situation in Example 11.3.4 can be modeled readily as an explicit linear program. Nevertheless, its representation as a network has the advantage that it offers computationally efficient algorithms for solving the problem. Indeed, expressing network situations as an explicit linear program usually results in disproportionately large models, with obvious computational disadvantages.

The model illustrated in Example 11.3.4 is known as the *capacitated network flow model.* Its special solution algorithm is actually rooted in the primal-dual theory of linear programming. However, the algorithm, which is designed to take advantage of the special network structure of the model, is more efficient than that based on the simplex method solution.

The capacitated network flow model can be specialized to represent three other common network models:

1. The transportation/assignment/transshipment model
2. The shortest-route model
3. The maximum-flow model

The capacitated model can be specialized to describe the *transportation model* and the *assignment model* in the following two manners:

1. The source nodes are linked directly to the destination nodes.
2. The minimum arc capacity is zero and its maximum capacity is infinity.

The *transshipment model* requires the same changes as in the transportation model except that the flow from a source to a destination can occur by way of one or more transshipping nodes.

In the *shortest-route model,* we seek to determine the shortest path between a source and a destination linked by a network of nodes. For example, on the U.S. map there are numerous routes that connect Los Angeles to New York passing through different cities. The capacitated model can be specialized to the shortest-route model in the following manner:

- The source node ships one unit from the source and receives one unit at the destination.
- All arcs have no capacity limits.
- The cost per unit of flow now represents the distance between nodes.

The *maximum-flow model* can be obtained from the capacitated model by effecting the following four changes:

1. Each arc has an upper-bound capacity that represents the maximum flow in the arc.
2. The amount shipped from the source node equals the amount received at the destination node.
3. A direct arc links the source and the destination nodes.
4. The unit flow cost in all arcs is zero, except for the link from the source to the destination, where it must be infinite.

Integer Linear Programming

Integer linear programming is a regular linear program in which some or all of the variables are restricted to integer values. This seemingly simple change in the structure of the model

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leads to a highly inefficient (and mostly unreliable) solution algorithm. To date, despite nearly 4 decades of research in the area of integer programming, there does not exist a single algorithm that can consistently solve all integer programming problems. This is in contrast with linear programming for which the simplex algorithm (and more recently the interior point algorithm) have shown highly consistent behavior for solving models of any size.

To appreciate the computational difficulty associated with integer programming, we use a graphical example to demonstrate the two most prominent methods for solving such problems.

EXAMPLE 11.3.5 *Consider the following model:*

$$\text{Maximize } z = 7x_1 + 10x_2$$

subject to

$$-x_1 + 3x_2 \leq 6$$

$$7x_1 + x_2 \leq 35$$

$$x_1, x_2 \geq 0 \text{ and integers}$$

In Fig. 11.3.3 the marked dots in the continuous solution space represent the feasible integer points of the problem.

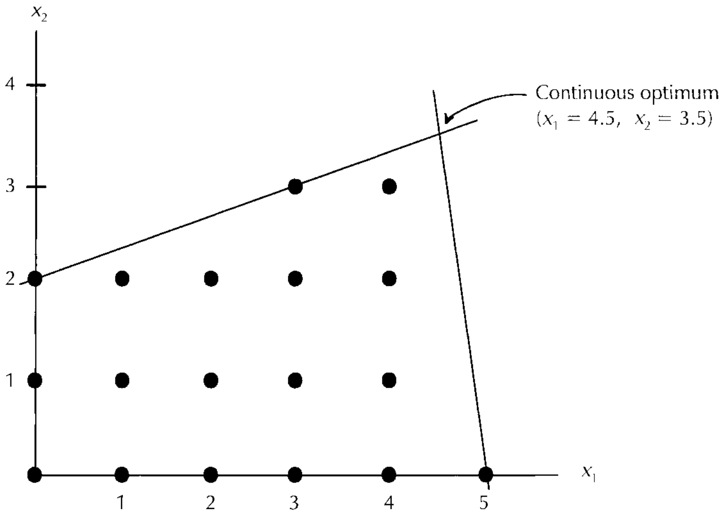

FIGURE 11.3.3 Feasible points of the integer linear program.

Two solution algorithms are available for solving the problem:

1. *Cutting plane*
2. *Branch and bound*

The crux of either method is to start the algorithm at the continuous linear programming optimum. The rationale behind this choice is that there is a greater likelihood that the integer optimum could be located close to the continuous optimum. The two procedures then modify the continuous space by systematically eliminating parts of it that do not include any feasible integer points, in a manner that the corner point of the modified space defines the desired optimum *integer point. The modifications are carried out iteratively, with each modification essentially resulting in formulating and solving a continuous linear program by the simplex method.*

Figure 11.3.4 demonstrates the cutting-plane algorithm. *The procedure starts at the continuous optimum at point A, which is determined by solving the problem as a continuous linear program. From the simplex tableau associated with point A, we generate cut I and impose it on the original feasible space. The new optimum occurs at point B. Because the solution at B is still a noninteger, an additional cut, cut II, is generated from the last optimum tableau. This new cut, together with cut I, now leads to the new optimum solution at point C. The process ends at point C because the point has all integer values.*

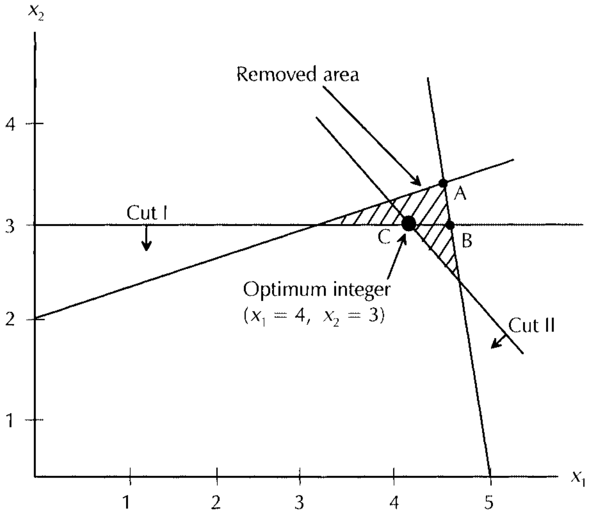

FIGURE 11.3.4 Effect of application of cuts to the continuous solution space.

In the illustration in Fig. 11.3.4, only two cuts are used to obtain the integer optimum. This result may give the impression that the number of generated cuts equals the number of integer variables. This is not true! Indeed, the convergence proof of the cutting-plane algorithm only ensures that the number of cuts needed to generate the optimum is finite. Computational experience with the algorithm has shown that, in general, one cannot predict the number of cuts based on the size of the problem. An additional computational difficulty arises because the cuts are generated from the fractional *values in the simplex tableau. The fact that these fractions (e.g.,* $^1/_7$ *and* $^1/_{13}$*) cannot be represented* exactly *on the computer, gives rise to roundoff error, which does adversely impact the theoretical foundation on which the cut is generated. The roundoff problem associated with the application of the cuts has rendered them less useful in practice. Indeed, none of the commercial codes available for solving integer linear programs rely solely on the cutting-plane method. Instead, the majority of the commercial codes are based on the* branch-and-bound algorithm, *which we will discuss next.*

Figure 11.3.5 demonstrates the application of the branch-and-bound algorithm to the example used to illustrate the cutting method. As in the cutting-plane method, the procedure starts at the continuous optimum at point A ($x_1 = 4.5$, $x_2 = 3.5$)*. From this information, we know that there are no feasible integer values in the ranges* ($4 < x_1 < 5$) *and* ($3 < x_2 < 4$)*. Arbitrarily targeting* x_1 *as the variable that we want to "integerize" (alternatively, we could select* x_2*), we can impose the following restrictions, one at a time, on the original solution space:* $x_1 \leq 4$ *or* $x_1 \geq 5$*.*

The successive application of these two mutually exclusive constraints creates two separate problems. In this case, we say that the branching variable x_1 *has created the two subproblems represented by nodes 1 and 2 in Fig. 11.3.5. By solving each subproblem as a linear program, we obtain the following solutions:*

Node 1. $x_1 = 5, x_2 = 0, z = 35$

Node 2. $x_1 = 4, x_2 = 3.33, z = 61.33$

The solution at node 1 is all integer. This means that we have encountered an integer-feasible solution, which may or may not be optimum. All we can say at this point is that we have a feasi-

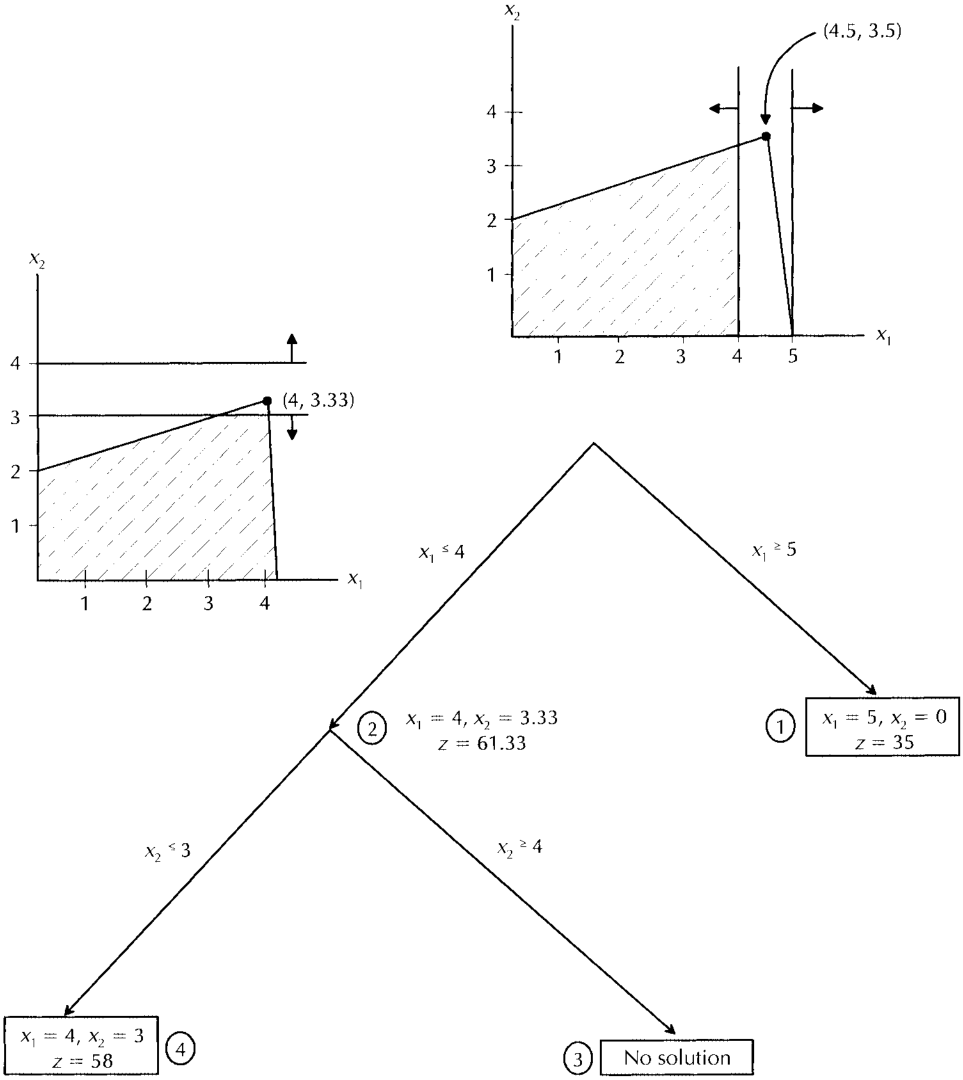
x_2
(4.5, 3.5)
4
3
2
1
1
2
3
4
5
x_1
x_2
4
3
2
1
(4, 3.33)
1
2
3
4
x_1
$x_1 \le 4$
$x_1 \ge 5$
2
$x_1 = 4, x_2 = 3.33$
$z = 61.33$
1
$x_1 = 5, x_2 = 0$
$z = 35$
$x_2 \le 3$
$x_2 \ge 4$
$x_1 = 4, x_2 = 3$
$z = 58$
4
3
No solution

FIGURE 11.3.5 Branch-and-bound tree.

ble integer solution whose objective value is $z = 35$. *In essence, in our search for the optimum solution, any node that can be shown not to yield an objective value better (i.e., higher) than* $z = 35$ *must not be explored any further, and hence must be discarded. This means that the solution at node 1 provides a* lower bound *on the optimum value of* z.

Looking at node 2, we notice that its $z = 61.33$*, which is higher than the current lower bound,* $z = 35$. *Thus, it is possible that the subproblems that can be created from node 2 may include a better integer solution. To that end, our new* branching variable *must be* x_2 *because its value at node 2 (= 3.33) is not an integer. This selection creates the two subproblems corresponding to branches* $x_2 \leq 3$ *and* $x_2 \geq 4$*, respectively.*

In Fig. 11.3.5, we see that the branch $x_2 \leq 3$ *(together with* $x_1 \leq 4$*) leads to an infeasible solution. Thus, no further branching is possible from this node. The remaining branch,* $x_2 \leq 3$ *(together with* $x_1 \leq 4$*) gives the feasible integer solution* $x_1 = 4$, $x_2 = 3$, *and* $z = 58$. *This is a better integer than the one encountered at node 1. Thus, the new lower bound is changed to* $z = 58$.

At this point, we note in Fig. 11.3.5 that all of the nodes of the search tree have been investigated. Thus, the solution associated with the current lower bound is the optimum; that is, $x_1 = 4$, $x_2 = 3$, *and* $z = 58$ *is optimum.*

Computational experience shows that the branch-and-bound procedure is more reliable for solving integer programs than the cutting-plane algorithm. This does not mean, however, that, in an absolute sense, branch-and-bound is an efficient algorithm. Indeed, the efficiency of the algorithm relies strongly on the decisions we make in selecting the next node to be investigated and on selecting the variable to be branched at each node. Unfortunately, there are no consistently reliable rules that we can use for making such decisions. This discussion points to an inherent weakness in the design of integer-programming algorithms; namely, we are never assured that we will be able to find the optimum integer solution in a reasonable amount of computational time.

The computational difficulties that typify integer-programming algorithms have lead to suggestions that one should solve the problem as a mere linear program and then round the continuous solution intelligently to the closest integer values. This idea is plausible when we deal with variables that logically lend themselves to rounding (e.g., number of machines or number of workers). There are situations where rounding is not acceptable. Typically, this occurs when we deal with yes-no decisions (e.g., in a capital budgeting situation, the problem reduces to selecting or not selecting a project). In such cases, an exact integer solution is necessary.

Goal Programming

All the models presented in the preceding sections deal with the optimization of a *single* objective function. In some situations, it may be necessary to deal with *multiple* (conflicting) objectives. In these cases, it may be impossible to find a single solution that satisfies all the goals of the proposed model. Instead, we may opt to prioritize the different goals in a specific order of importance, and then attempt to find a solution that will satisfy as many of these goals as possible. This is what *goal programming* does.

EXAMPLE 11.3.6 *The admission office of ABC University has set the following admission requirements for the new freshman class:*

- *The size of the class must be at least 1200 students.*
- *The average American College Test (ACT) score must be 25 or higher.*
- *The international students must constitute at least 10 percent of the incoming class.*
- *The male-female ratio is at least 1:1.*
- *The out-of-state students must constitute at least 20 percent of the incoming class.*

Past experience shows that the male-female ratios for in-state, out-of-state, and international applicants are 1:1, 3:2, and 7:1, respectively. The ACT scores among in-state, out-of-state, and international students are 27, 26, and 23, respectively.

To formulate this problem, define x_1, x_2, *and* x_3 *as the number of in-state, out-of-state, and international freshmen admitted to the university. The constraints of the problem are constructed as follows:*

$$x_1 + x_2 + x_3 \geq 1200$$

$$27x_1 + 26x_2 + 23x_3 \geq 25(x_1 + x_2 + x_3)$$

$$x_3 \geq 0.1(x_1 + x_2 + x_3)$$

$$0.5x_1 + 0.4x_2 + 0.125x_3 \geq 0.5x_1 + 0.6x_2 + 0.875x_3$$

$$x_2 \geq 0.2(x_1 + x_2 + x_3)$$

Next, we simplify the constraints to a format that has a constant right-hand side. Because we do not know in advance whether these constraints will be satisfied, we convert each inequality into an equation by adding $(s_i^+ - s_i^-)$ *to the left-hand side of constraint* i ($i = 1, 2, \ldots, 5$)*, where* s_i^+ *and* s_i^- *are nonnegative variables. The new constraints are now given as follows:*

$$x_1 + x_2 + x_3 + s_1^+ - s_1^- = 1200$$

$$2x_1 + x_2 - 2x_3 + s_2^+ - s_2^- = 0$$

$$-x_1 - x_2 + 9x_3 + s_3^+ - s_3^- = 0$$

$$0.2x_2 + 0.75x_3 + s_4^+ - s_4^- = 0$$

$$0.2x_1 - 0.8x_2 + 0.2x_3 + s_5^+ - s_5^- = 0$$

$$\text{all variables} \geq 0$$

In the new formulation, we would be tempted to satisfy the goal of each constraint as much as possible. For example, in the first constraint, if s_1^+ *is positive, the minimum requirement for the size of the freshman class is not met, whereas if* s_1^- *is positive, then the requirement is oversatisfied. An investigation of all the constraints would show that the goals of the model can be met (as much as possible) by using the following* goals *or objectives:*

Goal 1. *Minimize* s_1^+.
Goal 2. *Minimize* s_2^+.
Goal 3. *Minimize* s_3^+.
Goal 4. *Minimize* s_4^-.
Goal 5. *Minimize* s_5^-.

Note that goals 4 and 5 seek to minimize s_4^- *and* s_5^-*, respectively, because their constraints before conversion to equations are of the type* ≤*. The first three constraints are of the type* ≥*.*

To solve the problem, we must first prioritize the given goals to reflect their relative degree of importance. Once this is done, we have two ways to solve the problem:

1. *The weights method*
2. *The preemptive method*

In the weights method, *each goal is assigned a weight depending on its relative importance. For example, in the present example, and on a scale of 1 to 5, the following weights may be assigned* *to the different goals: 5 for goal 1, 4 for goal 2, 3 for goals 3 and 4, and 2 for goal 5. Based on this information, a combined objective function may be constructed as follows:*

$$\text{Minimize } z = 5s_1^+ + 4s_2^+ + 3(s_3^+ + s_4^-) + 2s_5^-$$

Using this weighted objective function, the problem is then solved as an ordinary linear program.

The preemptive method *differs from the weights method in that the optimization process is carried out using one goal at a time and in a preset order of priority. Based on the weights used in the weights method, it is reasonable to assume that the order of priority for the different goals is specified (from highest to lowest) as follows:*

Goal 1 _ Goal 2 _ Goal 3 _ Goal 4 _ Goal 5

The optimization process then calls for solving a linear program with goal 1 (minimize $z = s_1^+$*) as the objective function and using the set of equality constraints specified for the problem. The next linear program to be solved uses goal 2 (minimize* $z = s_2^+$*) for its objective function subject to the same set of constraints. However, the optimization of the goal 2 problem is carried out without deteriorating the optimum value of goal 1. An easy way to accomplish this result is as follows. Suppose that the minimum value of goal 1 as determined by the first linear program is* $s_1^+ = c$*, where* c *is a numeric constant. The solution of the goal 2 problem will not deteriorate the goal 1 optimum solution if we include the following additional constraint in the goal 2 problem:*

$$s_1^+ \leq c$$

The procedure is repeated until the goal 5 problem is optimized.

Note that the successive linear programs must include the necessary additional constraint(s) that will prevent the deterioration of higher-priority goals. This does not mean, however, that a feasible solution that satisfies *all* the goals is guaranteed. In other words, a higher-priority constraint may make it impossible to satisfy a lower-priority goal. In such a case, it will be necessary to relax one or more goals before a feasible solution can be found, or simply to declare that it is impossible to satisfy all the goals simultaneously.

Proponents of goal programming claim that the single-objective linear program is a subset of the multiobjective goal programming. Yet, goal programming is designed primarily to find a feasible solution that satisfies a set of (possibly conflicting) goals. In this regard, it is not an optimization technique. Indeed, there are situations where a better solution (in terms of lower cost or higher profit) can be found while satisfying all the goals of the problem. In addition, from the computational standpoint, methods (such as that based on the so-called *column-dropping rule*) have been proposed for solving goal-programming problems. These algorithms are unnecessarily cumbersome and can be replaced by the simpler methods we have proposed in this section.

NONLINEAR PROGRAMMING ALGORITHMS

When George Dantzig first introduced the concept of linear programming in a meeting of the Econometric Society in 1948, he was told (disapprovingly) that the real world is nonlinear rather than linear. Though linear programming has been used with tremendous success to approximate a whole range of applications, the fact remains that the real world is largely nonlinear. From this standpoint, operations researchers have always been interested in developing algorithms that can solve the unadulterated nonlinear problems. Unfortunately, efforts in this area have not been totally successful. The nonlinear problem has proven to be computationally very difficult. Indeed, to date there does not exist a single algorithm that can be used to find the global optimum of the general nonlinear problem. Instead, we only have a number of special cases for which efficient computational algorithms exist.

The objective of this section is to explain why the nonlinear problem is computationally difficult. At the same time, the presentation provides information about available algorithms that deal with special nonlinear cases.

The Karush-Kuhn-Tucker (KKT) Necessary Conditions

The general nonlinear programming problem is defined as follows:

$$\text{Maximize or minimize } f(x_1, x_2, \ldots, x_n)$$

subject to

$$g_i(x_1, x_2, \ldots, x_n) \le b_i, \quad i = 1, 2, \ldots, m$$

$$x_1, x_2, \ldots, x_n \ge 0$$

There are no special restrictions on the characteristics of the functions f and g_i $(i = 1, 2, \ldots, m)$.

Unlike linear programming where the linearity of the model guarantees that the problem will always have a global optimum, in nonlinear problems, no such guarantee can be established in advance unless the model's solution space and objective function can be shown to satisfy specific conditions. In particular, a nonlinear problem can be shown to possess a global optimum if, and only if, the conditions shown in Table 11.3.4 are satisfied.

TABLE 11.3.4 Conditions for a Global Optimum of Nonlinear Problem

	Required conditions	
Sense of optimization	Objective function	Solution space
Maximization	Concave	Convex
Minimization	Convex	Convex

If a nonlinear model possesses these properties, then the nonlinear algorithms will converge to the global optimum. Unfortunately, though available mathematical theory does provide conditions for testing the convexity of the solution space and the convexity/concavity of the objective function, these conditions are too analytically intractable to be useful computationally. Thus, in general, unless one can prove in advance that the nonlinear model possesses a global optimum, these is no way to tell whether a nonlinear programming algorithm will be converging to a local or a global optimum.

The difficult nature of the given conditions has given rise to a new set of conditions that may be easier to implement in practice. These new conditions check the convexity/concavity of the constraint functions g_i $(i = 1, 2, \ldots, m)$, rather than checking the convexity of the solution space itself. In this regard, the new conditions are a subset of the general conditions given previously.

The only unifying theory in nonlinear programming is given by the so-called *Karush-Kuhn-Tucker necessary conditions (KKT)*. These conditions are necessary but not sufficient. The only way we can establish sufficiency is by showing that the nonlinear model satisfies the conditions given previously regarding the convexity/concavity of the objective function and the convexity of the solution space.

Types of Nonlinear Algorithms

Available nonlinear programming algorithms can be divided into the following three main categories:

1. Transformation methods
2. Gradient search methods
3. Penalty methods

In the *transformation methods,* the original model is replaced by another model that is more tractable analytically. An excellent example of the application of this method is *quadratic programming,* where the objective function is strictly quadratic and the constraints are strictly linear. By applying the KKT necessary conditions presented previously, we obtain a linear program whose solution is optimum for the quadratic model (provided that we can establish that the original model has a global optimum). Another application deals with *geometric programming,* which is a highly nonlinear model whose functions satisfy special properties. By using the duality theory, we can construct a new *unconstrained* model whose solution provides the optimum for the original problem.

Gradient search methods determine the optimum point by following the path of steepest ascent (maximization) or descent (minimization) of the objective function within the feasible solution space. The steepest ascent/descent is determined by the gradient (slope) of the objective function at specified points in the solution space. The solution is obtained in iterations, with each iteration improving the objective value as much as possible along the path of the gradient. The algorithm terminates when new improvements in the objective value fall within prespecified tolerance limits.

The *penalty method* converts the nonlinear model into an unconstrained problem by specifying a new objective function that is highly penalized if the solution point at any iteration moves closer to the boundary of the solution space. In this respect, the penalty method is applicable only when it is known that the optimum solution occurs in the *interior* of the solution space. As with all nonlinear programming algorithms, the penalty method does not guarantee that the global optimum will be found. Rather, and depending on the properties of the model, the algorithm may be trapped at a local optimum point.

DYNAMIC PROGRAMMING

Dynamic programming is designed primarily to improve the computational efficiency by decomposing the original problem into smaller subproblems. The procedure typically solves the problem in *stages,* with each stage involving exactly one optimization variable. The computations associated with the successive stages are linked together through *recursive equations* in a manner that will guarantee yielding a feasible solution for the entire problem.

EXAMPLE 11.3.7 *The application of dynamic programming can be illustrated by the* shortest-route problem. *Figure 11.3.6 represents the different routes between cities 1 and 7. The distance between two adjoining cities is shown on the connecting arc. It is desired to determine the* shortest *route between cities 1 and 7.*

The network in Fig. 11.3.6 is divided into four stages that correspond to the order in which computations are carried out. Starting at node 1, we see that stage 1 includes nodes 2 and 3. Thus, we compute the following:

Shortest distance to node 2 = 2

Shortest distance to node 3 = 4

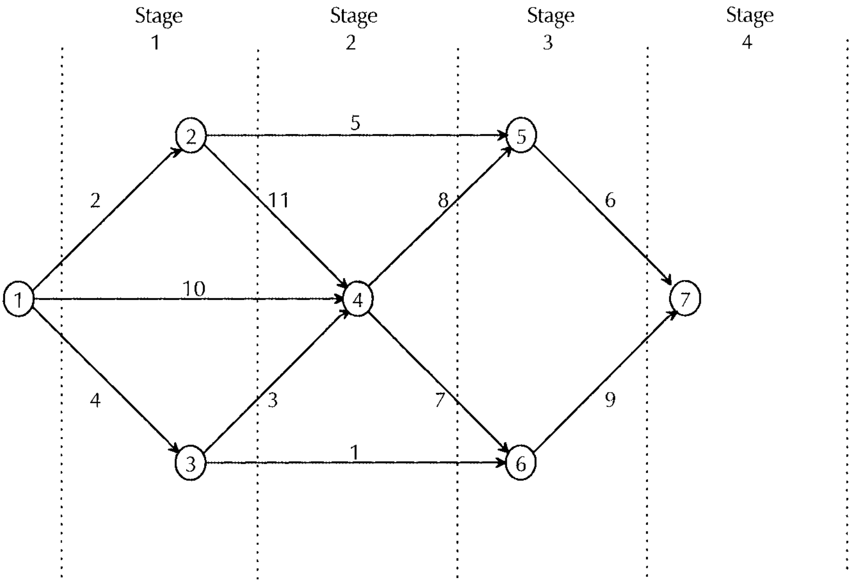

FIGURE 11.3.6 Network representation of the shortest-route problem.

Next, we move to stage 2, which happens to include node 4 only. The associated computations are as follows:

$$\begin{pmatrix}\text{Shortest distance}\\ \text{to node 4}\end{pmatrix} = \min\begin{cases}(\text{Shortest distance to node 2}) + 11\\ (\text{Shortest distance to node 1}) + 10\\ (\text{Shortest distance to node 3}) + 3\end{cases}$$

$$= \min\begin{cases}2 + 11 = 13\\ 0 + 10 = 10\\ 4 + 3 = 7\end{cases}$$

$$= 7 \text{ (Coming from node 3)}$$

Stage 3 includes nodes 5 and 6, and the associated computations are given as follows:

$$\begin{pmatrix}\text{Shortest distance}\\ \text{to node 5}\end{pmatrix} = \min\begin{cases}(\text{Shortest distance to node 2}) + 5\\ (\text{Shortest distance to node 4}) + 8\end{cases}$$

$$= \min\begin{cases}2 + 5 = 7\\ 7 + 8 = 15\end{cases}$$

$$= 7 \text{ (Coming from node 2)}$$

$$\begin{pmatrix}\text{Shortest distance}\\ \text{to node 6}\end{pmatrix} = \min\begin{cases}(\text{Shortest distance to node 3}) + 1\\ (\text{Shortest distance to node 4}) + 7\end{cases}$$

$$= \min\begin{cases}4 + 1 = 5\\ 7 + 7 = 14\end{cases}$$

$$= 5 \text{ (Coming from node 3)}$$

The last stage, stage 4, includes node 7 only. The associated computations are as follows:

$$\begin{pmatrix}\text{Shortest distance}\\ \text{to node 7}\end{pmatrix} = \min\begin{cases}(\text{Shortest distance to node 5}) + 6\\ (\text{Shortest distance to node 6}) + 9\end{cases}$$

$$= \min\begin{cases}7 + 6 = 13\\ 5 + 9 = 14\end{cases}$$

$$= 13 \text{ (Coming from node 5)}$$

The last set of computations shows that the shortest distance between nodes 1 and 7 is 13 (miles). To complete the solution we need to determine the associated route. We can see from the last set of calculations that node 7 is reached from node 5. The equation for node 5 shows that it must be reached from node 2, which finally must be linked to node 1. Thus, the associated optimal route is 1–2–5–7.

The preceding calculations can be summarized in terms of a *recursive equation.* Assume that d_{ij} is the distance between nodes i and j, and let u_j define the shortest distance from node 1 to node j, where $i, j = 1, 2, \ldots, 7$. Then, the recursive equation for finding the shortest route can be written as follows:

$$u_j = \min_i (u_i + d_{ij})$$

In this equation, the shortest distance (u_j) node j is computed only after u_i to each node i that precedes node i has been computed. For example, in the network of Example 11.3.7, the determination of u_4 at stage 2 requires that u_1, u_2, and u_3 be computed first at stage 1.

The main unifying theory in dynamic programming is the *principle of optimality.* It says that an optimum decision at each stage can depend only on the optimal solution of the immediately preceding stage. This principle allows us to decompose a model into stages properly. Observe, however, that dynamic programming is not concerned with how the subproblem at each stage is optimized. In general, one may have to use such algorithms as nonlinear programming or other techniques to solve the subproblem. The main contribution of dynamic programming lies in decomposing the original (complex) model into analytically simpler subproblems rather than in providing details about how the subproblem is solved numerically. In this regard, some individuals argue that the principle of optimality may be too powerful to be computationally feasible. This means that whereas dynamic programming attempts to simplify the nature of the problem we are trying to solve through decomposition, it does not guarantee that the resulting subproblems are solvable.

The computational difficulty associated with dynamic programming is compounded when each stage involves two or more constraints. In this case, the local computations at each stage may become difficult. For this reason, dealing with two or more constraints at each stage of the computation is sometimes referred to as the *curse of dimensionality.*

HEURISTIC PROGRAMMING

Heuristics are rules of thumb that can assist us in finding a *good* feasible solution rather than an optimum solution. We use heuristics when it is difficult or impossible to find an optimizing algorithm for the problem. Heuristics may also be used to replace optimizing algorithms that have poor computational efficiency. Such is the case with the integer-programming algorithms.

Example 11.3.8 is designed to demonstrate the application of heuristics to integer-programming problems.

EXAMPLE 11.3.8 *Consider the following problem:*

$$\textit{Maximize } z = 7x_1 + 9x_2$$

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subject to

$$-x_1 + 3x_2 \le 6$$

$$14x_1 - 8x_2 \le 35$$

$$x_1, x_2 \ge 0 \text{ and integer}$$

The general idea is to start with a feasible integer point. Then, an integer variable having the best rate of increase in the objective function is chosen and its value increased as much as the feasibility of the solution space allows. At this point, the next best integer variable (from the standpoint of its contribution to the objective value) is selected and its value again increased as much as feasibility would allow. This process is repeated as long as the value of the objective function can be improved.

Figure 11.3.7 gives a graphical representation of the heuristic. Starting at the origin (0, 0), we choose x_2 *because it has a higher objective coefficient. The constraints of the linear program show that* x_2 *can be increased to the integer value* $6/3 = 2$*. Fixing* $x_2 = 2$*, we next select* x_1 *for possible increase. The constraints show that* x_1 *can be increased up to* $[35 + (2 \times 8)]/14 = 3.64$*. In integer terms, this means that* x_1 *can be increased to level 3. Now, the solution is at point (2, 3). From that point, we can increase* x_2 *to level 3, and this will be followed by increasing* x_1 *to level 4. At point (4, 3), no further integer improvements are possible, and the process ends with* ($x_1 = 4$, $x_2 = 3$) *as the best available integer solution.*

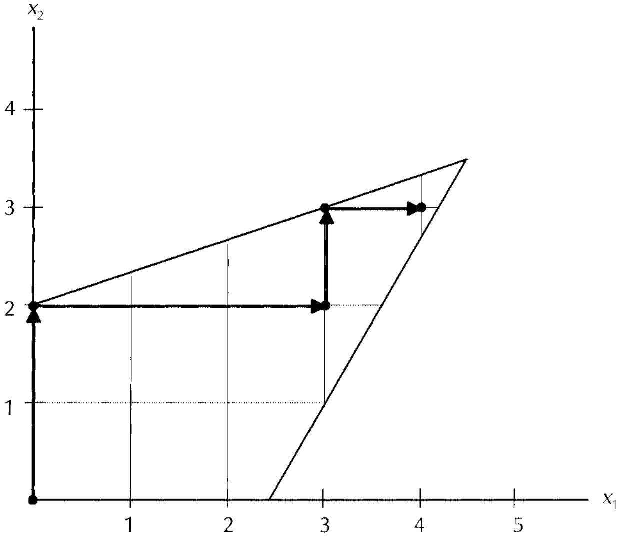

FIGURE 11.3.7 Example of heuristic search for integer solution.

In Example 11.3.8, the well-behaved heuristic happens to produce the optimum integer solution. In general, heuristics may not be well behaved or optimum. Take the graphical example in Fig. 11.3.8. Starting at the origin, the first step of the heuristic can trap the solution at point ($x_1 = 5, x_2 = 0$), from which no further improvements can be made in the objective value. In this case, it is suggested that the value of x_1 be arbitrated back to a smaller value ($x_1 = 4$) from which a heuristic path can be found to reach the better solution point ($x_1 = 4, x_2 = 2$). This

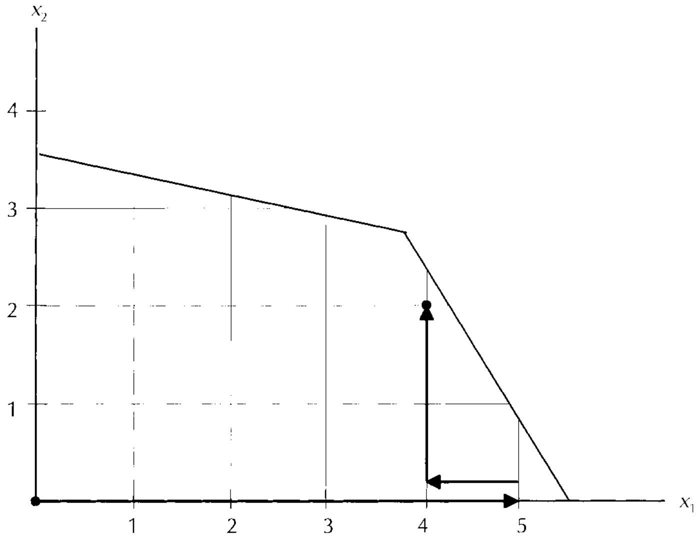

FIGURE 11.3.8 Backtracking in heuristic integer search.

observation points to the difficulties that are associated with heuristics, particularly when one deals with more than two variables.

Heuristics have been used as independent solution algorithms. In other cases, they are used to enhance the computational efficiency of an exact algorithm. For example, in the branch-and-bound algorithm for integer programming, a crucial piece of information that does affect the efficiency of the algorithm is the initial bound on the optimum value of the objective function. The tighter this initial bound, the higher the likelihood that a larger percentage of subproblems will not be examined explicitly, and hence the more computationally efficient is the algorithm. From this standpoint, a heuristic can be used to find a good feasible solution for the integer problem, which may then be used to establish a tight bound on the value of the objective function.

SUMMARY

This chapter has described the most important optimization algorithms. A general conclusion is that linear programming is by far the most efficient algorithm available in the operations research arsenal. It also happens to offer a wide variety of successful applications. On the other end of the spectrum, there are the algorithms of integer and nonlinear programming. Though we can boast a number of integer-programming algorithms that are known to converge to the optimum solution in a finite number of iterations, our computational experience with these algorithms has not been satisfactory, in the sense that to date there does not exist a computer code that can solve integer problems consistently. In nonlinear programming, we continue to be lacking in both theory and in computations. The only unifying theory available in nonlinear programming is that conveyed by the Karush-Kuhn-Tucker conditions. These conditions are necessary but not sufficient, and any algorithm based on these conditions can only guarantee a local rather than global optimum, unless we can establish a priori that the nonlinear problem possesses a unique optimum.

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BIOGRAPHY

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CHAPTER 11.4

APPLICATIONS OF QUEUING THEORY

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Queues or waiting lines, bottlenecks, and various other congestion-related phenomena leading to delays exist throughout virtually all types of production and service systems. Examples include traffic flows at intersections, toll booths, bank teller stations, plant in-process inventories, and innumerable other settings in which randomly occurring demands are to be satisfied by some service mechanism. This chapter provides a framework and summarizes the basic models and methods for analyzing queues.

First we present a framework for general queuing systems, including measures of effectiveness and performance. Next we explain the elementary Markov queuing models and follow up with the more advanced models. The current state of the art in queuing theory relies heavily on Markov chain models and steady-state probability distributions. Finally, we provide useful approximations for dealing with some of the difficult and not so fundamental conditions and end with some summary remarks.

A GENERAL FRAMEWORK FOR QUEUING MODELS

A queuing system is characterized over time *t* by an arrival process, a service process, and a set of environmental conditions that include the queuing discipline and any physical constraints that might apply to the system components.

The ingredients, or components, of a queuing system are customers, servers, and some facilities manager. While in most applications these components are people, there are many systems in which one or more are machines.

System Performance

Each person associated with a queuing system is generally trying to optimize something. Customers awaiting service, feeling that their time could be better spent elsewhere, are normally discontent with prolonged waits. They therefore want to minimize waiting time, and unless the service is pleasurable, they want to minimize their total time in the system. Servers are bounded on the one side by boredom when task demands are low and on the other side by stress when task demands are high. Ideally, the server workload is coordinated to some suitable pace or rate. The service facility manager usually benefits from maximizing the amount and quality of service provided by the facility. When the queue length becomes large, the manager becomes concerned about adverse effects on quality, throughput, and customer satisfaction.

With the multiple points of view that exist in any queuing system, several measures are necessary in order to specify overall system effectiveness. The following are the common measures used to characterize queuing systems:

1. Number of customers in the system
2. Number of customers in the queue
3. Total waiting time in the system
4. Waiting time in the queue
5. Server idle time
6. Utilization of the system

In each case the performance measure will be some function of the arrival and service processes and the environmental conditions. Average values are typically used to represent the expectations of these measures. The most basic measure is the average number of customers in the system over time, to which we associate the system state. Transitions among these states (i.e., the number of customers at various points in time) will change due to the randomness of the arrival and service processes and the environmental conditions. In general, both are stochastic processes, and hence, for fixed *t*, each has an underlying probability distribution.

Classification of Queuing Systems

A standard classification and notation for queuing systems has been adopted from Kendall [1], which specifies a system according to a, b, c, d, and e. Each of these elements are defined in Table 11.4.1. Elements a and b correspond to the arrival and service processes, respectively, c represents the number of parallel service channels, d the constraint on the number of customers permitted to enter the queue, and e is the queue discipline. For the common cases where d is infinite and e corresponds to the first-in, first-out (FIFO) order of service, they are typically suppressed in this notation.

BASIC MARKOV QUEUING MODELS

Notation

c	Number of parallel servers
K	System capacity limit
L	Long-run average number in the system
L_q	Long-run average number in the queue
λ	Mean arrival rate
λ'	Effective mean arrival rate = $\sum \lambda_n p_n$
λ_n	Mean arrival rate given n in the system
μ	Mean service rate
μ_n	Mean service rate given n in the system

TABLE 11.4.1 Classification for Queuing Systems

Characteristic	Symbol	Definition
Interarrival time distribution (a)	M	Exponential
	D	Deterministic
	E_k	Erlang-k, $k = 1, 2, \ldots$
	H_k	Hyperexponential-k
	PH	Phase type
	GI	General independent
Service time distribution (b)	M	Exponential
	D	Deterministic
	E_k	Erlang-k
	H_k	Hyperexponential-k
	PH	Phase type
	G	General
Number of parallel servers (c)	$1, 2, \ldots, c$	
System capacity (d)	$1, 2, \ldots, K$	
Queue discipline (e)	FIFO	First in, first out
	LIFO	Last in, first out
	SIRO	Service in random order
	PR	Priority
	GD	General discipline

$o(\Delta t)$ Order Δt, $\lim_{\Delta t \to 0} o(\Delta t)/\Delta t = 0$

p_n Steady-state probability of n in the system

$p_n(t)$ Probability of n in the system at time t

W Long-run average waiting time in the system

W_q Long-run average waiting time in the queue

General Birth-Death Model

Many queuing situations can be modeled by a birth-death process, which is a special Markov process for which transitions among states are restricted to nearest neighbors, and hence jumps are not allowed. Associating arrivals as births and service completions as deaths and letting $X(t)$ represent the number of customers in the system at $t \geq 0$,

$$p_{in}(t) = P\{X(t) = n | X(0) = i\}$$

For convenience, we suppress the first subscript i from $p_{in}(t)$. For an interval $(t, t + \Delta t)$ with $n \geq 0$, the state transitions can be described by way of the following postulates:

1. $P\{\text{arrival in } \Delta t | n \text{ in system}\} = \lambda_n \Delta t + o(\Delta t)$
2. $P\{\text{service completion in } \Delta t | n \geq 1 \text{ in system}\} = \mu_n \Delta t + o(\Delta t)$
3. $P\{\text{more than one arrival or service in } \Delta t | n \text{ in system}\} = o(\Delta t)$
4. Arrivals and services are independent of each other

It follows from the Chapman-Kolmogorov equations that

$$\begin{aligned} p_n(t+\Delta t) = {} & [1-(\lambda_n+\mu_n)\Delta t + o(\Delta t)]p_n(t) \\ & + [\lambda_{n-1}\Delta t + o(\Delta t)]p_{n-1}(t) \\ & + [\mu_{n+1}\Delta t + o(\Delta t)]p_{n+1}(t) + o(\Delta t) \end{aligned}$$

from which it follows that

$$\begin{aligned} p'_n(t) &= \lim_{\Delta t \to 0} \frac{p_n(t+\Delta t) - p_n(t)}{\Delta t} \\ &= -(\lambda_n+\mu_n)p_n(t) + \lambda_{n-1}p_{n-1}(t) + \mu_{n+1}p_{n+1}(t) \end{aligned}$$

after taking the limit and simplifying. The initial condition is

$$p_n(0) = \begin{cases} 1, n = i \\ 0, n \neq i \end{cases}$$

Steady State Balance Equations. The differential Eq. (11.4.1) can be solved in principle for various sets of values (λ_n, μ_n), $n = 0, 1, \ldots$. For most queuing systems these solutions are typically quite complicated. The steady-state solutions, however, provide results based on equilibrium or long-run average conditions, and these can generally be obtained without much difficulty.

If steady-state probabilities exist as $t \to \infty$, $p'_n(t) \to 0$ and $p_n(t) \to p_n$ independent of t. Thus we obtain from Eq. (11.4.1) the balance equations:

$$0 = -(\lambda_n + \mu_n)p_n + \lambda_{n-1}p_{n-1} + \mu_{n+1}p_{n+1}$$

Solution Procedure. Given a particular set of values (λ_n, μ_n), $n = 1, 2, \ldots$, we solve Eq. (11.4.2) to find the steady-state probabilities (p_n: $n = 1, 2, \ldots$), from which we can compute the following steady-state performance measures:

Probability of an arrival going directly into service:

$$p_0 = 1 - \sum_{n=c}^{\infty} p_n \tag{11.4.3}$$

Average number in system:

$$L = \sum_{n=0}^{\infty} np_n \tag{11.4.4}$$

Average number in queue:

$$L_q = \sum_{n=c}^{\infty} (n-c)p_n \tag{11.4.5}$$

The waiting times can be obtained simply by applying Little's formula, $L = \lambda' W$, thus giving

Average waiting time in system:

$$W = \frac{1}{\lambda'} L \tag{11.4.6}$$

Average queuing time:

$$W_q = \frac{1}{\lambda'} L_q \tag{11.4.7}$$

Little's formula applies to most systems provided the average arrival rate reflects the *effective arrival rate* that actually flows into service.

Simple Poisson Models

For the basic Poisson queuing model, the interarrival times are iid (i.e., independent and identically distributed) exponential with mean $1/\lambda$, and service times iid exponential with mean $1/\mu$. For the case of the single-server M/M/1 system, the birth-death coefficients are

$$\lambda_n = \lambda \qquad n \geq 0$$

$$\mu_n = \mu \qquad n \geq 1$$

Substituting into the balance Eq. (11.4.2),

$$0 = -\lambda p_0 + \mu p_1 \qquad n = 0$$

$$0 = -(\lambda + \mu)p_n + \mu P_{n+1} + \lambda p_{n-1} \qquad n \geq 1$$

from which we obtain

$$p_1 = \frac{\lambda}{\mu} p_0$$

$$p_{n+1} = \frac{\lambda + \mu}{\mu} p_n - \frac{\lambda}{\mu} p_{n-1} \qquad n \geq 1$$

Solving recursively, we get

$$p_1 = \left(\frac{\lambda}{\mu}\right) p_0$$

$$p_2 = \left(\frac{\lambda}{\mu}\right)^2 p_0$$

$$\cdots$$

$$p_j = \left(\frac{\lambda}{\mu}\right)^j p_0$$

Since the steady-state probabilities p_j, $j = 1, 2, \ldots$, sum to 1, letting $\rho = \lambda/\mu$, we get

$$1 = p_0 \sum_0^\infty \rho^j = \frac{p_0}{1 - \rho} \qquad |\rho| < 1$$

since ρ^j is an infinite geometric series; thus $p_0 = 1 - \rho$ and the steady-state distribution is

$$p_n = (1 - \rho)\rho^n \qquad n = 0, 1, 2, \ldots$$

The expected number in the system under steady-state conditions is found by

$$L = \sum_0^\infty n(1 - \rho)\rho^n = (1 - \rho)\rho \sum_1^\infty n\rho^{n-1}$$

$$= (1 - \rho)\rho \frac{d}{d\rho}\left(\frac{\rho}{1 - \rho}\right)$$

or

$$L = \frac{\rho}{1 - \rho}$$

For the expected number in the queue,

$$L_q = \sum_1^\infty (n-1)p_n = L - \sum_1^\infty p_n = L - \rho$$

or

$$L_q = \frac{\rho^2}{1-\rho} = \frac{\lambda\rho}{\mu-\lambda}$$

Alternatively, we note that

$$L_q = L - E[\text{number in service}] = L - \rho$$

From Little's formula the expected waiting times are

$$W = \frac{1}{\lambda}L = \frac{1}{\mu-\lambda}$$

$$W_q = \frac{1}{\lambda}L_q = \frac{\lambda}{\mu^2-\lambda\mu}$$

Table 11.4.2 provides results for the systems arising from the various conditions on the number of servers and constraints on arriving customers and servers.

M/M/1. Customers arrive at a first-aid station in accordance with a Poisson process with a mean rate of two patients per hour. Patients are treated in the order of arrival by a nurse whose treatment time is distributed exponentially with a mean of 15 minutes per patient. Since arrivals are Poisson, the interarrival time distribution is exponential. Here we have $\lambda = 2, \mu = 4$, and hence $\rho = 1/2$, which is less than 1. The steady-state probability distribution from Table 11.4.2*a* is

$$p_n = (1-\rho)\rho^n = \frac{1}{2}\left(\frac{1}{2}\right)^n \qquad n = 1, 2, \ldots$$

from which we obtain

$$L = \frac{\rho}{1-\rho} = \frac{1/2}{1-1/2} = 1 \text{ patient}$$

$$L_q = \frac{\rho^2}{1-\rho} = \frac{(1/2)^2}{1-1/2} = 1/2 \text{ patient}$$

$$W = L/\lambda = 1/2 \text{ hr}$$

$$W_q = L_q/\lambda = \left(\frac{1}{2}\right)/2 = 1/4 \text{ hr}$$

M/M/1/**K:** ***Finite Capacity.*** The interarrival times for customers seeking service at a beauty salon are distributed exponential with a mean of 20 minutes. Service is provided on a first-come, first-served basis by a beautician whose service time is exponentially distributed with a mean of 15 minutes. The shop has five chairs for waiting customers (not counting the customer being served), and it is assumed that potential customers enter only if a chair is available. Here we have $K = 6$ with

$$\lambda = \left(\frac{1}{20}\right)60 = 3 \text{ customers/hr}$$

and

$$\mu = \left(\frac{1}{15}\right)60 = 4 \text{ customers/hr}$$

TABLE 11.4.2*a* Simple Steady-State Poisson Queuing Models

Measure	M/M/1	M/M/1/K	M/M/1, finite population = m	M/M/c
Birth-death coefficients	$\lambda_n = \lambda, n \geq 0$ $\mu_n = \mu, n \geq 1$	$\lambda_n = \begin{cases} \lambda, & n \leq K-1 \\ 0, & n > K \end{cases}$ $\mu_n = \mu, n \geq 1$	$\lambda_n = \begin{cases} (m-n)\,\lambda, & 0 \leq n \leq m \\ 0, & n \geq m \end{cases}$ $\mu_n = \begin{cases} \mu, & 1 \leq n \leq m \\ 0, & n > m \end{cases}$	$\lambda_n = \lambda, n \geq 0$ $\mu_n = \begin{cases} n\mu, & 1 \leq n \leq c \\ c\mu, & n \geq c \end{cases}$
p_n	$(1-\rho)\rho^n \; n = 0, 1, 2, \ldots$	$\rho^n p_0 \; n = 0, \ldots, \mathrm{K}$	$\dfrac{m!}{(m-n)!}\rho^n p_0 \; n = 1, \ldots, m$	$\begin{cases} \dfrac{(\lambda/\mu)^n}{n!} p_0, & n \leq c \\ \dfrac{(\lambda/\mu)^n}{c!\, c^{n-c}} p_0, & n \geq c \end{cases}$
p_0	$1-\rho$	$\begin{cases} \dfrac{1-\rho}{1-\rho^{K+1}}, & \rho \neq 1 \\ \dfrac{1}{K+1}, & \rho = 1 \end{cases}$	$1/\sum_0^m \left[\dfrac{m!}{(m-n)!}\left(\dfrac{\lambda}{\mu}\right)^n\right]$	$\left[\sum_{k=0}^{c-1} \dfrac{(\lambda/\mu)^k}{k!} + \dfrac{(\lambda/\mu)^c}{c!\left(1-\dfrac{\lambda}{c\mu}\right)}\right]^{-1}$
λ'	λ	$\dfrac{\lambda(1-\rho^K)}{1-\rho^{K+1}}$	$\lambda(m-L)$	λ
L	$\dfrac{\rho}{1-\rho}$	$\dfrac{\rho[1-(K+1)\rho^K + K\rho^{K+1}]}{(1-\rho)(1-\rho^{K+1})}$	$m - \dfrac{\lambda}{\mu}(1-p_0)$	$\left[\dfrac{(\lambda/\mu)^c \lambda\mu}{(c-1)!(c\mu-\lambda)^2}\right] p_0 + \dfrac{\lambda}{\mu}$
L_q	$L-\rho$	$L - \dfrac{\rho(1-\rho^K)}{1-\rho^{K+1}}$	$m - \dfrac{\lambda+\mu}{\mu}(1-p_0)$	$\left[\dfrac{(\lambda/\mu)^c \lambda\mu}{(c-1)!(c\mu-\lambda)^2}\right] p_0$
W	$\dfrac{1}{\mu-\lambda}$	$\dfrac{\rho[1-(K+1)\rho^K + K\rho^{K+1}]}{\lambda(1-\rho)(1-\rho)^K}$	$\dfrac{m\mu - \lambda(1-p_0)}{\lambda^2(1-p_0)}$	$\left[\dfrac{\mu(\lambda/\mu)^c}{(c-1)!(c\mu-\lambda)^2}\right] p_0 + \dfrac{1}{\mu}$

TABLE 11.4.2*b* Simple Steady-State Poisson Queuing Models

Measure	M/M/∞	M/M/c/K, finite capacity	M/M/c, finite population $= m$
Birth-death coefficients	$\lambda_n = \lambda, n \geq 0$ $\mu_n = n\mu, n \geq 1$	$\lambda_n = \begin{cases} \lambda, 0 \leq n \leq K \\ 0, n \geq K \end{cases}$ $\mu_n = \begin{cases} n\mu, 0 \leq n < c \\ c\mu, c \leq n \leq K \end{cases}$	$\lambda_n = \begin{cases} (m-n)\lambda \; 0 \leq n \leq m \\ 0, n \geq m \end{cases}$ $\mu_n = \begin{cases} n\mu, 0 \leq n < c \\ c\mu, n \geq c \end{cases}$
p_n	$\dfrac{(\lambda/\mu)^n e^{-\lambda/\mu}}{n!} \; n \geq 0$	$\begin{cases} \dfrac{(\lambda/\mu)^n}{n!} p_0, 0 \leq n \leq c \\ \dfrac{(\lambda/\mu)^n}{c!c^{n-c}} p_0, c < n \leq K \end{cases}$	$\begin{cases} \dbinom{m}{n}(\lambda/\mu)^n p_0, 0 \leq n < c \\ \dbinom{m}{n} \dfrac{n!}{c!c^{n-c}} (\lambda/\mu)^n p_0, c \leq n \leq m \end{cases}$
p_0	$\left[\sum_0^\infty \dfrac{(\lambda/\mu)^n}{n!}\right]^{-1} \to e^{-\lambda/\mu}$	$p_0 = \left[\sum_{n=0}^{c-1} \dfrac{(\lambda/\mu)^n}{n!} + \dfrac{(\lambda/\mu)^c}{c!}\left(\dfrac{1-\rho^{K-c+1}}{1-\rho}\right)\right]^{-1}$ $\rho = \lambda/c\mu \neq 1$	$\left[\sum_{n=0}^{c-1} \dbinom{m}{n}(\lambda/\mu)^n + \sum_{n=c}^{m} \dbinom{m}{n} \dfrac{n!}{c!\,c^{n-c}}(\lambda/\mu)^n\right]^{-1}$
λ'	λ	$\lambda(1-p_K)$	$\lambda(m-L)$
L	λ/μ	$L_q + \sum_0^{c-1} np_n + c\left(1 - \sum_0^{c-1} p_n\right)$	$\sum_{n=0}^{c-1} n\dbinom{m}{n}(\lambda/\mu)^n + \dfrac{1}{c!}\sum_{n=c}^{m} n\dbinom{m}{n}\dfrac{n!}{c^{n-c}}(\lambda/\mu)^n$
L_q	0	$\dfrac{(\lambda/\mu)^c \rho p_0}{c!(1-\rho)^2}\{1 - [(K-c)(1-\rho)+1]\,\rho^{K-c}\}$	$L - c + p_0 \sum_{n=0}^{c-1}(c-n)\dbinom{m}{n}(\lambda/\mu)^n$
W	$\dfrac{1}{\mu}$	$\dfrac{L}{\lambda(1-p_K)}$	$\dfrac{L}{\lambda(m-L)}$

Therefore, $\rho = 3/4$. So, from Table 11.4.2*a,* the steady-state distribution is

$$p_n = \frac{\rho^n(1-\rho)}{1-\rho^{K+1}} = \frac{(0.75)^n(1-0.75)}{1-(0.75)^7}$$
$$= 0.289(0.75)^n$$

Computing the average number of customers in the system,

$$L = \frac{0.75[1-7(0.75)^6+6(0.75)^7]}{0.25[1-(0.75)^7]} = 1.92 \text{ customers}$$

and in the queue,

$$L_q = 1.92 - \frac{0.75[1-(0.75)^6]}{1-(0.75)^7} = 1.21 \text{ customers}$$

the effective arrival rate is

$$\lambda' = \frac{3[1-(0.75)^6]}{1-(0.75)^7} = 2.85 \text{ customers/hr}$$

Therefore average waiting time in the beauty salon is

$$W = L/\lambda' = 1.92/2.85 = 0.67 \text{ hrs} = 40.4 \text{ min}$$

and the time spent waiting to be served is

$$W_q = L_q/\lambda' = 1.21/2.85 = 0.42 \text{ hrs} = 25.5 \text{ min}$$

M/M/1: Finite Population. A plant produces plastic containers by five blow-molding machines. Machine failures occur as Poisson events (i.e., with exponentially distributed interarrival times) at a mean rate of 0.1 machines per hour and are repaired by a mechanic who requires time that is exponentially distributed with a mean of 4 hours. Thus we have $m = 5$, $\lambda = 0.1$, $\mu = 0.25$, and therefore $\rho = 1/25$. From Table 11.4.2*a,* we obtain

$$p_0 = \left[\sum_0^5 \frac{5!}{(5-n)!}\left(\frac{0.1}{0.25}\right)^n\right]^{-1} = 0.07$$

and

$$p_n = \frac{5!}{(5-n)!}(0.4)^n p_0 \qquad n = 0, \ldots, 5$$

Therefore,

$$L_q = 5 - \frac{0.1+0.25}{0.25}(1-0.07) = 3.64 \text{ machines}$$
$$L = 3.64 + (1-0.07) = 4.61 \text{ machines}$$

The effective arrival rate is

$$\lambda' = 0.1(5-4.61) = 0.039 \text{ machines/hr}$$

from which we get

$$W = 4.61/0.039 = 118.2 \text{ hrs}$$

$$W_q = 3.64/0.039 = 93.3 \text{ hrs}$$

***M/M/*c.** Customers arrive at a bank according to a Poisson process at a mean rate of 30 per hour and are served by one of three tellers if available; otherwise they join a queue. Customers are served in the order of their arrival by the first available teller. Each teller takes an exponentially distributed amount of time for each customer with a mean of 5 minutes, and this is independent of the other tellers.

With $c = 3$ servers, $\lambda = 30$ customers/hr, and $\mu = (1/5)60 = 12$ customers/hr, we have $\rho = \lambda/c\mu = 30/[3(12)] = 5/6 < 1$. Computing p_0,

$$p_0 = \left[\frac{(30/12)^0}{0!} + \frac{(30/12)^1}{1!} + \frac{(30/12)^2}{2!} + \frac{(30/12)^3}{3!(1-5/6)}\right]^{-1} = 0.045$$

Hence

$$p_n = \begin{cases} \dfrac{(2.5)^n}{n!}(0.045) & n \le 3 \\ \dfrac{(2.5)^n}{6 \times 3^{n-3}}(0.045) & n \ge 3 \end{cases}$$

It follows that

$$L_q = \left[\frac{(30/12)^3(30)(12)}{2![3(12) - 30]^2}\right](0.045) = 3.52 \text{ customers}$$

$$W_q = 3.52/30 = 0.12 \text{ hrs} = 7.03 \text{ min}$$

$$W = 0.12 + 1/12 = 0.20 \text{ hrs} = 12.2 \text{ min}$$

and

$$L = (30)(0.20) = 6.0 \text{ customers}$$

M/M/∞: Unlimited Servers. Customers arrive at a large self-service merchandise center in accordance with a Poisson process with a mean rate of 10 customers per hour. The service time of each customer is iid exponential with a mean of 1/4 hour.

Thus, we have $\lambda = 10$ customers/hr and $\mu = 4$ customers/hr, and from Table 11.4.2*b,* we get

$$p_n = \frac{(10/4)^n e^{-10/4}}{n!} = \frac{2.5^n(0.082)}{n!} \qquad n = 0, 1, \ldots$$

which is the Poisson distribution. With an infinite number of servers, there is no queue; therefore, the long-run average number in the system is the average number in service. Thus

$$L = 10/4 = 2.5 \text{ customers}$$

and, from Little's formula,

$$W = 1/4 = 0.25 \text{ hours}$$

M/M/*c/K: *Finite Capacity. A shipyard has four berthing areas to receive ships that arrive for repairs according to a Poisson process with a mean rate of 1.5 per month. Each ship is serviced by one of two available crews who work on the ships in the order of their arrival. The service times for each crew are independent and exponentially distributed with a mean of 1 month per ship.

With $\lambda = 1.5$, $\mu = 1$, and $c = 2$, we have $\rho = 0.75$ and, for $K = 4$ in Table 11.4.2*b,*

$$p_0 = \left[\sum_0^1 \frac{(1.5/1)^n}{n!} + \frac{(1.5/1)^2}{2!}\left(\frac{1-(1.5/2)^{4-2+1}}{1-(1.5/2)}\right)\right]^{-1} = 0.606$$

Thus,

$$p_n = \begin{cases} \dfrac{(1.5)^n}{n!}(0.606) & n = 0, 1, 2 \\ \dfrac{(1.5)^n}{2 \times 2^{n-2}}(0.606) & n = 3, 4 \end{cases}$$

The steady-state average number of ships in the queue for service is

$$L_q = \frac{(1.5/1)^2(0.75)(0.606)}{2!(1-0.75)^2} \times \{1 - [(4-2)(1-0.75)+1](0.75)^{4-2}\} = 1.28 \text{ ships}$$

and the average number in the shipyard is

$$L = L_q + c - \sum_{0}^{c-1}(c-n)p_n$$

$$= 1.28 + 2 - \left\{2(0.606) + \frac{(1.5)^1}{2}(0.606)\right\} = 2.98 \text{ ships}$$

With the effective arrival rate of

$$\lambda' = 1.5(1-p_4) = 1.5\left[1 - \frac{(1.5)^4}{2!2^2}(0.606)\right]$$

the average times a ship spends awaiting service and in the system, respectively, are

$$W_q = L_q/\lambda' = 1.28/0.92 = 1.38 \text{ months}$$

and

$$W = L/\lambda' = 1.61/0.92 = 1.74 \text{ months}$$

M/M/*c: *Finite Population. A paper manufacturer produces paper on five machines, each of which breaks down at random times, with the time between failures exponentially distributed with a mean of 50 hours. Each breakdown is serviced by one of two available mechanics in the order of failure. Repair times are exponentially distributed with a mean of 10 hours.

The parameters are $m = 5$ machines, $c = 2$ mechanics, $\lambda = 1/50$, and $\mu = 1/10$ machines per hour. From Table 11.4.2*b* we have

$$p_0 = \left[\sum_{n=0}^{1}\binom{5}{n}(1/5)^n + \sum_{n=2}^{5}\binom{5}{n}\frac{n!}{2!2^{n-2}}(1/5)^n\right]^{-1} = 0.402$$

from which we compute the steady-state probabilities

$$p_n = \begin{cases} \dbinom{5}{n}(0.2)^n(0.402) & n = 0, 1 \\ \dbinom{5}{n} n!(0.2)^n/2 \times 2^{n-2}(0.402) & n = 2, \ldots, 5 \end{cases}$$

The average number of machines down for repair is

$$L = (0.402)\left[\sum_{n=0}^{1} n\binom{5}{n}(0.2)^n + \frac{1}{2!}\sum_{n=2}^{5} n\binom{5}{n}\frac{n!}{2^{n-2}}(0.2)^n\right] = 0.912 \text{ machines}$$

and the number down awaiting service is

$$L_q = 0.912 - 2 + (0.402)\sum_{0}^{1}(2-n)\binom{5}{n}(0.2)^n = 0.12 \text{ machines}$$

The effective arrival rate is

$$\lambda' = \frac{1}{50}(5 - 0.912) = 0.082 \text{ machine/hr}$$

Hence, the average total down time for a machine is

$$W = 0.912/0.082 = 11.2 \text{ hr}$$

and from Little's formula, the average time spent waiting for repair is

$$W_q = \frac{1}{\lambda'}L_q = 0.12/0.082 = 1.46 \text{ hr}$$

Queues with Behavioral Influences

A variety of behavioral characteristics can be incorporated in the general birth-death model by particular choices of (λ_n, μ_n) in Eq. (11.4.2). These state-dependent models can be such that service, arrivals, or both are influenced behaviorally by the state of the system. Closed-form results are an exception rather than the rule for state-dependent models. However, once the steady-state distributions are known, the performance measures can be computed directly using the results of Eqs. (11.4.3) through (11.4.7).

M/M/1: Discouraged Arrivals. Interarrival times iid exponential with mean $1/\lambda$, single server with service times iid exponential with mean $1/\mu$, arriving customers balk or are diverted from the stream of arrivals entering the system according to a discouragement parameter $\beta > 0$, with the birth-death coefficients of

$$\lambda_n = \frac{\lambda}{(n+1)^\beta} \qquad n \geq 0$$

$$\mu_n = \mu \qquad n \geq 1$$

From Eq. (11.4.2), it follows that the steady-state probabilities are given by

$$p_n = \frac{(\lambda/\mu)^n}{(n!)^\beta}p_0 \qquad n \geq 0$$

where

$$p_0 = \left[\sum_{n=0}^{\infty}\frac{(\lambda/\mu)^n}{(n!)^\beta}\right]^{-1}$$

Note that for the special case of $\beta = 0$, we have the basic M/M/1 model. Otherwise, the flow of arrivals declines with increasing n at a rate dictated by β.

Example. Arrivals to a single-server service system occur in accordance with a Poisson process at a rate of 10 customers per hour whenever the queue is empty. Otherwise, arriving customers enter the system at a rate that decreases inversely with the square root of the number of customers in the queue plus one (i.e., $(n + 1)^{1/2}$ and $\beta = ½$). Service times are iid exponential with a mean of 1/15 hours per customer. It follows from Eq. (11.4.8) that

$$p_0 = \left[\sum_{n=0}^{\infty}\frac{(2/3)^n}{(n!)^{1/2}}\right]^{-1} \cong 0.463$$

Therefore,

$$p_n = \frac{(2/3)^n}{\sqrt{n!}}(0.463)$$

It follows that

$$L = \sum_{n=0}^{\infty} \frac{n(2/3)^n(0.463)}{\sqrt{n!}} = 0.883 \text{ customers}$$

and from Little's formula

$$W = 0.883/10 = 0.0883 \text{ hrs} = 5.3 \text{ min}$$

M/M/1: Binomial Arrivals. Let arrivals and services be such that the birth-death coefficients are

$$\lambda_n = \begin{cases} \dfrac{N-n}{N(n+1)} & 0 \le n < N \\ 0 \qquad n \ge N \end{cases}$$

$$\mu_n = \mu \qquad n \ge 1$$

Haight [2] showed that for these conditions the steady-state probability distribution is

$$p_n = \binom{N}{n}\left(\frac{1}{1+N\mu}\right)^n\left(\frac{N\mu}{1+N\mu}\right)^{N-n} \qquad n = 0, 1, \ldots, N \tag{11.4.9}$$

which is the binomial distribution with parameter (i.e., probability of success) $1/(1 + Nm)$.

Thus it follows that the long-run average number in the system is

$$L = \frac{N}{1+N\mu} \tag{11.4.10}$$

and, from Eq. (11.4.5), the average number in the queue simplifies to

$$L_q = \frac{N(1+N\mu)^N - (N\mu)^N}{(1+N\mu)^N} \tag{11.4.11}$$

The effective arrival rate for this system is

$$\lambda' = \sum_0^{N-1} \frac{n(N-n)}{N(n+1)} \tag{11.4.12}$$

and from Little's formula (i.e., Eqs. (11.4.6) and (11.4.7))

$$W = \left(\frac{N}{1+N\mu}\right) \Big/ \sum_0^{N-1} \frac{n(N-n)}{N(N+1)} \tag{11.4.13}$$

$$W_q = \left(\frac{N(1+N\mu)^N - (N\mu)^N}{(1+N\mu)^N}\right) \Big/ \sum_0^{N-1} \frac{n(N-n)}{N(N+1)} \tag{11.4.14}$$

M/M/1: Two-Speed Service. Interarrival times iid exponential with mean $1/\lambda$, and a single Markov server whose mean rate μ_a shifts to μ_b when J customers are in the system. The birth-death coefficients are

$$\lambda_n = \lambda \qquad n \ge 0$$

$$\mu_n = \begin{cases} \mu_a & 1 \le n < \\ J \end{cases}$$

From Eq. (11.4.2) it follows (see Ref. 3) that

$$p_n = \begin{cases} (\lambda/\mu_a)^n p_0, \; 0 \le n < J \\ \dfrac{\lambda^n}{\mu_a^{J-1}\mu_b^{n-J+1}} p_0, \; n \ge J \end{cases} \tag{11.4.15}$$

with

$$p_0 = \left[\frac{1-\rho_a^J}{1-\rho_a} + \frac{\rho_b \rho_a^{J-1}}{1-\rho_b}\right]^{-1} \qquad \rho_a = \lambda/\mu_a \qquad \rho_b = \lambda/\mu_b < 1$$

The steady-state average number of customers in the system is given by

$$L = p_0 \left\{ \frac{\rho_a[1 + (J-1)\rho_a^J - J\rho_a^{J-1}]}{(1-\rho_a)^2} + \frac{\rho_b \rho_a^{J-1}[J - (J-1)\rho_b]}{(1-\rho_b)^2} \right\} \tag{11.4.16}$$

from which the number in the queue can then be computed from Eq. (11.4.5)

$$L_q = L - (1 - p_0) \tag{11.4.17}$$

The average times in the system and queue can then be computed from Little's formula.

M/M/*c: *Channel Control. Interarrival times iid exponential with mean $1/\lambda$; service is provided by a team of c available parallel servers each with rate μ; after the first server, each additional server up to c is activated when the number in the system reaches each additional multiple of I. The birth-death coefficients are

$$\lambda_n = \lambda \qquad n \ge 0$$

$$\mu_n = \begin{cases} \mu & 1 \le n \le I \\ 2\mu & I < n \le 2I \\ & \cdots \\ (c-1)\mu & (c-2)\mathrm{I} < n \le (c-1)I \\ c\mu & n \ge cI \end{cases}$$

Giffin [4] provides the results for this model in terms of the function

$$K(n, i) = \frac{(\lambda/\mu)^n}{(i!)^I (i+1)^{n-iI}} \tag{11.4.18}$$

and

$$p_n = \begin{cases} K(n,i)p_0 & 0 \le n \le (i+1)I \qquad 0 \le \mathrm{i} \le \mathrm{c}-1 \\ \dfrac{(\lambda/\mu)^n}{(c!)^I c^{n-cI}} p_0 & n > cI \end{cases} \tag{11.4.19}$$

with

$$p_0 = \left[\sum_{i=0}^{c-1} \sum_{n=iI}^{(i+1)I} K(n, i) + \frac{(\lambda/\mu)^{cI}}{(c!)^I (1 - \lambda/c\mu)}\right]^{-1}$$

The long-run average number of customers in the system is

$$L = \sum_{n=0}^{cI-1} np_n + \frac{(\lambda/\mu)^{cI} p_0}{(c!)^I} \left[\frac{\lambda/c\mu}{(1-\lambda/c\mu)^2} + \frac{cI}{1-\lambda/c\mu}\right] \tag{11.4.20}$$

The expected number of customers in service, S, is given by

$$E[S] = \sum_{i+1}^{c-1} \sum_{n=(i-1)I+1}^{iI} ip_n + c \sum_{n=(c-1)I+1}^{cI} p_n + \frac{c(\lambda/\mu)^{cI}}{(c!)^I}\left[\frac{1}{1-\lambda/c\mu-1}\right]p_0 \qquad (11.4.21)$$

from which the average number in the queue can be computed,

$$L_q = L - E[S] \qquad (11.4.22)$$

The long-run average number in the system and queue can be found by Little's formula.

Example. A bank operates with a team of four tellers each, with an average service time of 0.75 services per minute. When tellers are not occupied at the counter, they perform other clerical functions. Interarrival and service times are exponentially distributed, and the mean time between arrivals is 0.5 minutes. Management prefers that no more than three persons should have to wait in line before other tellers are assigned.

Here we have $c = 4$ tellers, $I = 3$ customers, $\lambda = 2$ customers/minute, $\mu = 0.75$ customers/minute, and hence $\lambda/\mu = 2.67$. Thus, from Eq. (11.4.18)

$$K(n, i) = \frac{2.67^n}{(i!)^3(i+1)^{n-3i}}$$

and

$$\begin{aligned} p_0 &= \left[\sum_{i=0}^{3} \sum_{n=3i}^{3(i+1)} K(n, i) + \frac{2.67^{12}}{(4!)^3(1-2.67/4)}\right]^{-1} \\ &= [K(0,0) + K(1,0) + K(2,0) + K(3,0) + K(3,1) + \ldots + K(12,3) + 28.5]^{-1} \\ &= 0.00245 \end{aligned}$$

Therefore, in Eq. (11.4.19), we have the following steady-state probability distribution:

$$p_n = \begin{cases} (0.00245)K(n, i) & 0 \le n \le 3(i+1) \qquad 0 \le i \le 3 \\ \dfrac{0.00245(2.67)^n}{(4!)^3 4^{n-12}} & n > 12 \end{cases}$$

M/M/c*: *Discouraged Arrivals/Pressured Service. Interarrival times iid exponential with mean $1/\lambda$, but arriving customers divert as the number in the system increases; c parallel servers each with iid exponentially distributed service time with mean that decreases (or increases) as the number in the system increases (decreases). Letting $\alpha > 0$ be a pressure coefficient of a server and $\beta > 0$ a discouragement coefficient for potentially arriving customers, the birth-death coefficients are

$$\lambda_n = \begin{cases} \lambda & 0 \le n < c \\ \left(\dfrac{c}{n+1}\right)^{\beta}\lambda & n \ge c \end{cases}$$

$$\mu_n = \begin{cases} n\mu & 1 \le n \le c \\ \left(\dfrac{n}{c}\right)^{n} c\mu & n > c \end{cases}$$

The steady-state probability distribution is given by

$$p_n = \begin{cases} \dfrac{(\lambda/\mu)^n}{n!} p_0 & 0 < n \le c \\ \dfrac{(\lambda/\mu)^n p_0}{c!(n!/c!)^{\gamma} c^{(1-\gamma)(n-c)}} & n > c \end{cases} \tag{11.4.24}$$

where $\gamma = \alpha + \beta$ and

$$p_0 = \left[\sum_{n=0}^{c-1} \frac{(\lambda/\mu)^n}{n!} + \frac{(\lambda/\mu)^c \sum_{n=c}^{\infty} (\lambda/\mu)^{n-c}}{c!(n!/c!)^{\gamma} c^{(1-\gamma)(n-c)}} \right]^{-1}$$

The results for this model were developed by Hillier, Conway, and Maxwell [5,6] who also provided tables for p_0, L, and L_q for various values of γ, c, and λ/μ.

ADVANCED MARKOV QUEUING MODELS

The models presented in the previous section allowed transitions to adjacent states only, and the state of the system was completely described by knowing the number of customers in the system. As a result, the balance equations for these systems were relatively simple recursive equations that could be solved readily. In this chapter the Markov property is maintained at each transition in the queuing process, but the transition is not necessarily to an adjacent state. As a result, the analysis required to determine steady-state probabilities and performance measures is more complicated. Some of the more useful results for non-birth-death Markov queuing models are summarized in this section. The interested reader is referred to Gross and Harris [3] for more details concerning their derivation.

$M/M^{[k]}/1$: Bulk Service. Arrivals to the system form a Poisson process with parameter λ. Service times are iid exponential with mean $1/\mu$ for a single server processing a batch of k customers. If there are $n < k$ in the system when the server is ready, the smaller batches are processed with the same service distribution applying to batch size k. Batches are selected on a FIFO basis and there is no restriction on queue size. We consider a single server here, but the extension to multiple servers is not difficult.

The steady-state balance equations for this system are as follows:

$$\begin{aligned} 0 &= \mu P_{n+K} - (\lambda + \mu) P_n + \lambda P_{n-1} \qquad n \ge 1 \\ 0 &= \mu P_k + \mu P_{k-1} + \ldots + \mu P_1 - \lambda P_0 \end{aligned} \tag{11.4.25}$$

The first equation indicates that the rate of entry into state n from state $n + k$ is m, the rate of batch completions. The second equation indicates that if a batch size less than k is being processed, the transition upon completion is to state zero. We will use operator methods to analyze these difference equations. A difference operator is such that, for example,

$$P_{n+2} = D^2 P_n$$

$$P_{n-1} = D^{-1} P_n$$

Thus, the first equation of Eq. (11.4.25) may be written as follows:

$$[\mu D^{(k+1)} - (\lambda + \mu) D + \lambda] P_n = 0 \qquad n \ge 0$$

The resulting operator equation possesses roots

$$r_1, r_2, \ldots, r_{k+1}$$

Rouche's theorem may be employed to show that only one root (r_0, say) is less than 1; thus,

$$P_n = cr_0^n \qquad n \geq 0, 0 < r_0 < 1 \tag{11.4.26}$$

Note that Eq. (11.4.26) has the same form as found in the M/M/1 queue analysis with the role of the traffic intensity ρ played by r_0. Hence, since

$$\sum P_n = 1$$

then

$$c = 1 - r_0 = P_0$$

and

$$P_n = (1 - r_0)r_0^n \qquad n \geq 0, 0 < r_0 < 1$$

The measures of performance are familiar, as well, such as

$$L = \frac{r_0}{1 - r_0}$$

Important to the analysis of this queuing model is the determination of r_0, which can be efficiently determined numerically using a method for finding the roots of polynomials.

M

M_i/M/1/Infinity/PRP: Preemptive Priority Queue. If the queue discipline selects the next customer for service based on attributes of the customer such that one customer may have priority over another, analysis becomes much more complex. Balance equations may still be constructed but are difficult to evaluate due to the increase in dimensionality; the state definition usually includes the number of each customer class in the queue and the classification of the customer in service. Measures of performance of a Markov priority queue are unaffected by priority structure (except waiting time, which becomes a function of priority class) as long as the selection rule is not a function of relative service time. A *preemptive* priority structure implies that a higher-ranking customer will interrupt the service of a lower-ranking customer immediately upon arrival. The lower-priority customer ultimately resumes service at the point of interruption or starts over again. With exponential service, each alternative is equivalent with respect to measures of performance; but this is not true for general service distributions. For more details on priority queues and their analysis, refer to Jaiswal [7].

Example. A company is selling time on its research parallel computer to outside customers with the understanding that internal customers may bump an outside customer's running job at any point (assuming the computer is completely dedicated to one job at a time). Computer runs average 6 hours for both internal and external customers and are exponentially distributed. Customers both in and outside the company request computer services according to a Poisson process at a rate of 1/8 per hour and 1/30 per hour, respectively. How similar are the response times for the two customer classes (queue plus service times)?

From the data,

$$\mu = \frac{1}{6} \qquad \lambda_1 = \frac{1}{8} \qquad \lambda_2 = \frac{1}{30}$$

Let k = number of priority classes = 2

$$a_j = \sum_{i=1}^{j} \frac{\lambda_i}{\mu} \qquad a_0 = 0$$

The expected time in the system for class *j* program is as follows:

$$W_j = \frac{1}{\mu}/(1 - a_{j-1})(1 - a_j)$$

$$W_1 = \frac{6}{(1-0)\left(1 - \frac{6}{8}\right)} = 24 \text{ hours (1 day)}$$

$$W_2 = \frac{6}{\left(1 - \frac{6}{8}\right)\left(1 - \frac{6}{8} - \frac{6}{30}\right)} = 480 \text{ hours (20 days)}$$

Thus, the company is not at all responsive to outside customers given present high-usage levels by the overall traffic intensity, as indicated by

$$\rho = \frac{6}{8} + \frac{6}{30} = 0.95$$

M_i/M/c/Infinity/NPRP: Nonpreemptive Priority Queue. In most situations where a customer priority structure is in place, customers of lower priority to an arriving customer are not preempted but are allowed to complete their service. Arrival from each priority class *i* form a Poisson process with rate λ_i and service time is iid exponential and common service rate to all priority classes of μ. Let

$$a_j = \sum_{i=1}^{j} \frac{\lambda_i}{c\mu} \qquad j = 1, \ldots, k$$

where k = number of priority classes.

$$a_o = 0 \qquad \rho = a_k \le 1$$

The probability of a customer having to wait for service is

$$P(n \ge c) = 1 - \sum_{n=0}^{c-1} P_n = 1 - P_0 \sum_{n=0}^{c-1} \frac{(\lambda/\mu)^n}{n!}$$

Using Table 11.4.2*a*, we get

$$P(n \ge c) = \frac{c(\lambda/\mu)^c}{c!(c - \lambda/\mu)} \left[\sum_{n=0}^{c-1} \frac{1}{n!}\left(\frac{\lambda}{\mu}\right)^n + \frac{1}{c!}\left(\frac{\lambda}{\mu}\right)^c \left(\frac{c\mu}{c\mu - \lambda}\right)\right]^{-1}$$

The mean waiting time in the queue for a class *j* customer is

$$W_{qj} = \frac{P(n \ge c)}{s\mu(1 - a_{j-1})(1 - a_j)}$$

Example. Consider the example given for the M_i/M/1/∞/PRP model. Under preemption, the priority 2 customer suffered severe delays. Let

$W_{qj}(\text{PRP})$ = mean waiting time in the queue for a class *j* customer under preemption

$= W_j - 1/\mu$

$W_{q1}(\text{PRP}) = 24 - 6 = 18$ hours

$W_{q2}(\text{PRP}) = 480 - 6 = 472$ hours

APPLICATIONS OF QUEUING THEORY

Similarly, employing Eq. (11.4.27),

$$W_{qj}(\text{NPRP}) = \frac{P(n \geq 1)}{\mu(1 - a_{j-1})(1 - a_j)}$$

$$W_{q1}(\text{NPRP}) = \frac{0.95}{\left(\frac{1}{6}\right)(1 - 0)\left(1 - \frac{6}{8}\right)} = 22.8 \text{ hours}$$

$$W_{q2}(\text{NPRP}) = \frac{0.95}{\left(\frac{1}{6}\right)\left(1 - \frac{6}{8}\right)\left(1 - \frac{6}{30}\right)} = 28.5 \text{ hours}$$

Thus, if outside users are allowed to complete their use of the computer once service begins, there is a dramatic improvement in their response time with only a modest degradation of the response time to the inside user.

EMBEDDED MARKOV CHAIN MODELS

In this section, the time between transitions in the queuing process no longer needs to be strictly exponentially distributed. As long as either the time between arrivals or the time to complete services is exponential, a Markov chain may be embedded in an otherwise, non-Markov process, and the computational tractability benefits of a Markov chain analysis are available to a certain degree. The Chapman-Kolmogorov equations are no longer a basis for the analysis for the resulting stochastic process, however. The following paragraphs will outline how an analysis of queuing systems with embedded Markov chains may be accomplished. For a more detailed discussion, the interested reader is referred to Gross and Harris [3].

M/G/1: Poisson Input, General Service. Such systems must be observed at a service completion. At that point the time to the next service completion is a random variable possessing a general distribution, and the time to the next arrival possesses an exponential distribution due to the memoryless property of the exponential. Thus, the transition process can be completely specified with a state description that includes only the number in the system, as in previous single-server systems. However, any number of arrivals may occur between service completions, leading to more computationally cumbersome analysis. Let x_n = number of customers in the system at departure point n and A_{n+1} = number of arrivals that occurred between departure point n and departure point $n + 1$. Then

$$x_{n+1} = \begin{cases} x_n - 1 + A_{n+1} & x_n \geq 1 \\ A_{n+1} & x_n = 0 \end{cases}$$

Dropping the subscript of A_n since the arrival process is not dependent on the service process, and denoting S as the service time variable, $B(t)$ and $b(t)$ as the service time CDF and PDF, respectively, we have

$$K_m = \text{probability of } m \text{ arrivals during } s = t$$

$$= \int_0^\infty P(A = m \mid S = t)dB(t)$$

Since the arrival process is Poisson,

$$P(A = m \mid S = t) = \frac{e^{-\lambda t}(\lambda t)^a}{a!}$$

The steady-state system size is measured and probabilities determined at departure points when a service is completed. Let

$$\pi_n = P\{n \text{ in system at a departure point in steady state}\}$$

To determine the steady-state probabilities, we must evaluate the following:

$$\pi_i = \pi_0 K_i + \sum_{j=1}^{i+1} \pi_j \mathrm{K}_{i-j+1} \qquad i = 0, 1, 2, \ldots$$

Defining generating functions for π_i and K_m as $\pi(z)$ and $K(z)$, respectively, multiplying each equation of Eq. (11.4.28) by z^i, and summing ultimately gives

$$\pi(z) = \frac{\pi_0(1-z)K(z)}{K(z)-z}$$

with $\pi_0 = 1 - \rho$. Generating function $\pi(z)$ may be inverted for the probabilities in one of the usual ways. If the inversion cannot be accomplished in closed form, a Maclaurin series expansion solution can be tedious, and a numerical solution is sought.

We can determine the expected number in the system by evaluating the following:

$$L = \frac{d\pi(z)}{dz}\Big|_{z=1} = \rho + \frac{\rho^2 + \lambda^2\sigma_s^2}{2(1-\rho)}$$

where σ_s^2 is the service time distribution variance. Equation (11.4.30) is known as the *Pollaczek-Khintchine formula.*

Example. An auto paint shop offers three levels of paint jobs: economy, classic, and supreme. The difference between the various paint jobs is the degree of surface preparation and the number of coats applied. As a result, the time required is 1 hour, 3 hours, and 5 hours, respectively. The proportion of customers requesting each level is 0.5, 0.4, and 0.1, respectively. Customers arrive according to a Poisson process at a rate of 0.25/hour. The shop does not wish to have more than one customer waiting more than 25 percent of the time. Are they meeting their goal?

In many realistic settings, data on service times is gathered in such a way that discrete distributions are formed based on the frequency that service times fall into prespecified intervals. Although the integral for K_m is usually difficult to evaluate for continuous $b(t)$, discrete b_t reduces the integration to a summation and greatly simplifies the remaining analysis for p_n. The summation is

$$K_m = \frac{1}{m!}\sum_{t=1}^{T} e^{-\lambda S_t}(\lambda S_t)^m b_t$$

which has generating function $K(z)$, and S_t is the service time associated with frequency class t. Simplifying Eq. (11.4.29) using this $K(z)$ leads to

$$\pi(z) = \frac{(1-\rho)\left[1 + \sum_{i=1}^{\infty}\left(\frac{C_i}{C_0 i!} - \frac{C_{i-1}}{C_0(i-1)!}\right)z^i\right]}{1 + \left(\frac{C_1 - C_0}{C_0}\right)z + \sum_{i=2}^{\infty}\frac{C_i}{C_0 i!}z^i}$$

where

$$C_i = \sum_{t=1}^{T} b_t e^{-\lambda S_t}(\lambda S_t)^i$$

We use the fact that the ratio of two power series is another power series,

$$\frac{1 + \sum_{i=1}^{\infty} a_i z^i}{1 + \sum_{i=1}^{\infty} b_i z^i} = \sum_{i=0}^{\infty} d_i z^i$$

where

$$d_i = \begin{cases} a_i - \sum_{j=1}^{i} b_j d_{i-j} & \text{if } i \geq 1 \\ 1 & \text{if } i = 0 \end{cases}$$

to generate an expression for the steady state system size probabilities

$$p_n = (1 - \rho) d_n \qquad n \geq 0$$

The auto paint shop has $T = 3$ frequency classes with associated service times $S_t = \{1, 3, 5\}$, probabilities $b_t = \{0.5, 0.4, 0.1\}$, $E(S_t) = 1/\mu = 2.2$ hours, and $\lambda = 0.25$/hours. Note that

$$a_i = \frac{C_i}{C_0 i!} - \frac{C_i - 1}{C_0 (i-1)!} \qquad i \geq 1$$

$$b_i = \begin{cases} \dfrac{C_i}{C_0 i!} & i \geq 2 \\ \dfrac{C_1 - 1}{C_0} & i = 1 \end{cases}$$

Evaluating the various constants, we get

$$C_i = (0.5)e^{-0.25(1)}(0.25)^i + (0.4)e^{-0.25(3)}[(0.25)(3)]^i + (0.1)e^{-0.25(5)}[(0.25)(5)]^i$$

$$= 0.3984(0.25)^i + 0.1889(0.75)^i + 0.0287(1.25)^{iC}$$

$$C_0 = 0.607 \qquad C_1 = 0.2749 \qquad C_1 = 0.1754$$

$$a_1 = \frac{0.2749}{(0.607)(1)} - \frac{0.607}{(0.607)(1)} = -0.5471$$

$$a_2 = \frac{0.1754}{(0.607)(2)} - \frac{0.2749}{(0.607)(1)} = -0.3084$$

$$b_1 = \frac{0.2749 - 1}{0.607} = -1.1946$$

$$b_2 = \frac{0.1754}{(0.607)(2)} = 0.1445$$

$$d_0 = 1$$

$$d_1 = -0.5471 - (-1.1945)(1) = 0.6474$$

$$d_2 = -0.3084 - (-1.1945)(0.6474) - (0.1445)(1) = 0.3204$$

Thus, the probability of more than one customer waiting is as follows:

$$P\{n \geq 3\} = \sum_{n=3}^{\infty} = 1 - p_0 - p_1 - p_2$$

$$= 1 - (1 - \rho)(d_0 + d_1 + d_2)$$

$$= 1 - \left(1 - \frac{25}{0.4545}\right)(1 + 0.6474 + 0.3204)$$

$$= 0.1145$$

which is less than 0.25; the shop's goal is realized.

M/G/c/c: Loss System. The steady-state system size distribution is as follows:

$$P_n = \frac{(\lambda/\mu)^n/n!}{\sum_{i=0}^{c}(\lambda/\mu)^i/i!} \qquad 0 \le n \le c \tag{11.4.31}$$

which is the truncated Poisson distribution and

$$L = (\lambda/\mu)(1 - P_c)$$

Equation (11.4.31) is valid for any general service time distribution, and p_c is often referred to as *Erlang's loss formula* (the probability of an arriving customer being turned away and lost to the system). If c is infinite, Eq. (11.4.31) reduces to

$$P_n = \frac{e^{-\lambda/\mu}(\lambda/\mu)^n}{n!} \qquad n \ge 0$$

associated with what is referred to as the *self-serve model,* since there are as many servers as there are potential customers.

Example. A 1000-bed hospital admits 800 patients each week, with arrivals forming a Poisson process. The average stay is for one week, with the time normally distributed and a variance of 2. What is the average patient population and what is the likelihood of an inadequate number of beds?

Note that $\lambda = 800$/week, $1/\mu = 1$ week, $c = 1000$ and is large. Thus, using Stirling's approximation for $n!$ (accurate for $n > 20$), we have

$$P_n = \frac{e^{-\lambda/\mu}\left(\dfrac{\lambda}{\mu}\right)^n}{\sqrt{2\pi n}\; n^n e^{-n}} = \frac{e^{n-\lambda/\mu}\left(\dfrac{\lambda}{n\mu}\right)^n}{\sqrt{2\pi n}}$$

A patient is turned away if all beds are occupied, which has probability

$$P_c = \frac{e^{c-\lambda/\mu}\left(\dfrac{\lambda}{c\mu}\right)^c}{\sqrt{2\pi c}} = \frac{e^{1000-800}(0.8)^{1000}}{\sqrt{2\pi(1000)}}$$

$$= 1.12(10)^{-12} \approx 0$$

which isn't very likely, at all! The expected number of occupied beds is equivalent to the expected number of busy servers

$$L = \frac{\lambda}{\mu}(1 - P_c) \approx \frac{\lambda}{\mu} = 800 \text{ occupied beds}$$

Note that the variance of the service distribution plays no role in this analysis.

APPROXIMATION METHODS

The more features attributed to a queuing model, the more complicated the analysis becomes. Balance equations become unwieldy (e.g., in the bulk queuing models) and the overall analysis becomes much more difficult as the Markov transition property is relaxed as it was for arrivals or for services discussed earlier in this chapter. For GI/G/*c* models, very little useful analytical results are available, and analysis must be based on numerical methods, simulation, or approximation. The latter of these approaches is the subject of this section. A number of techniques will be presented with illustrations using more general queuing models. For more details concerning these techniques, the interested reader is referred to Gross and Harris [3] and Tijms [8] and to the references given in them.

Asymptotic Expansion-Based Approximations

M/G/1. Except for the case of Markovian queuing models, the determination of $P\{W_q > x\}$ for more general queuing models is, typically, a formidable undertaking. However, in calculating $P\{W_q > x\}$, the entire distribution of W_q is not of interest, only its tail. In many practical cases, it is possible to fit an approximating exponential distribution to W_q that is most accurate for larger values of x. The parameters for this approximating exponential function are derived through an asymptotic analysis of $P\{W_q > x\}$. It is useful here to think of a customer bringing some number of units of work s to the queuing system that must be accomplished by the server before the customer leaves. The server is able to do σ units of work per unit time. The service time of the customer is s/σ. Let

V_n = number of units of work in the system just prior to the arrival of customer n

D_n = the delay in the queue of customer n

$$q(x) = \lim_{n\to\infty} P\{V_n > x\} \qquad x \ge 0$$

$$q(\sigma x) = \lim_{n\to\infty} P\{D_n > x\} \qquad x \ge 0$$

$$\rho = \frac{\lambda E(s)}{\sigma} = \frac{\lambda}{\mu}$$

The function $q(x)$ solves the following integro-differential equation:

$$\frac{dq(x)}{dx} = -\frac{\lambda}{\sigma}[1 - B(x)] + \frac{\lambda}{\sigma}q(x) - \frac{\lambda}{\sigma}\int_0^x q(x-y)b(y)dy \qquad x > 0 \tag{11.4.32}$$

for the case of a M/G/1 queue with $B(x)$ as the customer work requirement CDF.

It can be shown that Eq. (11.4.32) is related to a renewal equation, and that relationship is exploited to provide the following approximate solution:

$$q(x) \approx \gamma e^{-\delta x} \qquad \text{for large } x \tag{11.4.33}$$

where

$$\gamma = (1-\rho)\left\{\frac{\lambda\delta}{\sigma}\int_0^\infty y e^{\delta y}[1 - B(y)dy]\right\}^{-1} \tag{11.4.34}$$

and the value of δ is such that

$$\frac{\lambda}{\sigma}\int_0^\infty e^{\delta y}[1 - B(y)]dy = 1 \tag{11.4.35}$$

Even for relatively small values of x (in the range of $E(s)$ to $2E(s)$), Eq. (11.4.33) is reasonably accurate, especially when ρ is not too small (say, $\rho \geq 0.2$). A better estimate for $q(x)$ over all $x \geq 0$ can be derived by letting

$$q(x) = \alpha e^{-\beta x} + \gamma e^{-\delta x} \qquad x \geq 0 \tag{11.4.36}$$

and noting that

$$W_q = \int_0^\infty q(x)\,dx = \frac{\lambda E(s^2)}{2\sigma(1-\rho)} \tag{11.4.37}$$

and

$$q(0) = \rho \tag{11.4.38}$$

we get, after evaluating Eq. (11.4.36),

$$\alpha = \rho - \gamma \tag{11.4.39}$$

$$\beta = \alpha\left[\frac{\lambda E(s^2)}{2\sigma(1-\rho)} - \frac{\gamma}{\delta}\right]^{-1} \tag{11.4.40}$$

which is accurate if $\beta > \delta$ and $\rho \geq 0.2$.

In summary, to calculate $P\{W_q > x\}$ for the M/G/1 model, Eq. (11.4.35) must be solved for δ, typically using numerical quadrature to evaluate the integral as a polynomial and then finding the positive root of that polynomial equation. Numerical integration will usually be required to evaluate Eq. (11.4.34) for γ. If x is large, Eq. (11.4.33) can be evaluated; if not, Eqs. (11.4.39) and (11.4.40) give α and β to use in Eq. (11.4.36) for an estimate of $P\{W_q > x\}$.

M/G/1: Impatient Customers. Customers are willing to wait for service to begin for τ time units. If service has not begun, the customer *reneges,* or leaves the system and is lost. This represents a good model for perishable-goods inventory analysis. Let the amount of work each customer brings to the system possess a general distribution and the service rate equal σ units of work per unit time. Then

$$\begin{aligned} p &= \text{proportion of all customers who renege, given a waiting threshold of length } \tau \\ &\approx \frac{(1-\rho)(\alpha e^{-\beta\sigma\tau} + \gamma e^{-\delta\sigma\tau})}{1-\rho(\alpha e^{-\beta\sigma\tau} + \gamma e^{-\delta\sigma\tau})} \\ &\approx (1-\rho)\gamma e^{\delta\sigma\tau} \end{aligned} \tag{11.4.41}$$

if σt is large and if $\pi(t) < 0.01$. In addition,

$$\begin{aligned} W_q(\tau) &= \text{mean waiting in the queue, given a } \tau \text{ waiting threshold} \\ &\approx \frac{\dfrac{\alpha}{\sigma\beta} - \alpha\left[\dfrac{1}{\sigma\beta} + \rho\tau\right]e^{-\beta\sigma\tau} + \dfrac{\gamma}{\sigma\delta} - \gamma\left[\dfrac{1}{\sigma\delta} + \rho\tau\right]e^{-\delta\sigma\tau}}{1-\rho(\alpha_e^{-\beta\sigma\tau} + \gamma e^{-\delta\sigma\tau})} \end{aligned} \tag{11.4.42}$$

where δ, γ, α, and β are determined by Eqs. (11.4.35), (11.4.34), (11.4.39), and (11.4.40), respectively.

M/M/1/k: Finite Work Buffer Capacity. The arrival process of customers is Poisson with rate λ. Each customer brings some amount of work to be processed by the server, and the amount of work is exponentially distributed. The server processes the work at rate of σ/unit time. Only k units of work are allowed in the system at one time. An arrival bringing work in excess of buffer capacity is turned away. Let

$$\pi(k) = \text{proportion of customers turned away because of work buffer being at capacity } k$$

$$\approx \gamma e^{-\delta k} \tag{11.4.43}$$

for $\rho < 1$ and k such that $\pi(k) < 0.001$, where

$$\delta = \frac{1 - \rho}{E(s)} \tag{11.4.44}$$

$$\gamma = (1 - \rho)e^{-\rho} \tag{11.4.45}$$

M/D/1/k k$_0$: Finite Work Buffer Capacity. Arrivals bring along a fixed amount of work to be processed, and work in excess of capacity is turned away. Thus, δ is determined by finding the unique solution of

$$e^{\delta E(s)} = 1 + \frac{\delta\sigma}{\lambda} \tag{11.4.46}$$

where γ is given by

$$\gamma = (1 - \rho)[\delta E(s) - (1 - \rho)]^{-1} \tag{11.4.47}$$

and $\pi(k)$ is determined using Eq. (11.4.43).

Example. A facility that processes fresh oranges close to the groves has truckloads of oranges arriving according to a Poisson process at a rate of 85 trucks per day. Packaging is highly standardized and automated, with 100 truckloads being processed per day and negligible variation observed. If the oranges cannot be packaged in one day, they are squeezed for juice at lower unit profit. If more than 1 percent of the oranges have to be turned into juice, capacity will need to be increased. At 85 percent facility utilization, should there be any concern? At 98 percent utilization?

An M/D/1 model with "impatience" is used to answer these questions, with the reneging feature being the removal of oranges from the packaging option after one day in the queue. The data suggest that $\lambda = 85$ trucks/day, $\mu = 1/D = 100$ trucks/day, and $\tau = 1$ day. Calculating the parameters needed for the asymptotic approximation formulas, we solve for the root of Eq. (11.4.35) as follows:

$$(85)(e^{\delta(0.01)} - 1) - \delta = 0$$

giving $\delta = 31.6687$. Eq. (11.4.34) specializes to

$$\gamma = \frac{1 - \rho}{\delta D - (1 - \rho)}$$

$$= \frac{\left(1 - \frac{85}{100}\right)}{(31.67)(0.01) - \left(1 - \frac{85}{100}\right)} = 0.9$$

Solving Eqs. (11.4.39) and (11.4.40) gives

$$\alpha = 0.85 - 0.9 = -0.05$$

$$\beta = \frac{(-0.05)}{\frac{(85)(0.01)^2}{2(0.15)} - \frac{0.9}{31.67}} = 607.1$$

The steady-state proportion of all oranges that will be squeezed instead of packaged is given by Eq. (11.4.41),

$$\pi(\tau) = \pi(1) = \frac{(0.15)[(-0.05)e^{-590.12} + (0.9)e^{-31.67}]}{1 - (0.85)[(-0.05)e^{-590.12} + (0.9)e^{-31.67}]}$$

$$\approx (0.15)(0.9)e^{-31.67} = 2.38(10)^{-15}$$

or very little chance of it at all. If the plant is operating at 98 percent of capacity, then

$$\delta = 4.027 \qquad \gamma = 0.98667 \qquad \alpha = -0.00667 \qquad \beta = 34.129$$

and

$$\pi(1) = 0.000358 < 0.01$$

Thus, the plant's capacity need not be increased. The average amount of time a truckload of oranges waits to be processed when the plant is at 98 percent of capacity is given by Eq. (11.4.42)

$$\begin{aligned} W_q(\tau) = W_q(1) = \Bigg\{ & \frac{-0.00667}{34.129} - (-0.00667)\left[\frac{1}{34.129} + (0.98)(1)\right]e^{-34.129} \\ & + \frac{0.98667}{4.027} - (0.98667)\left[\frac{1}{4.027} + (0.98)(1)\right]e^{-4.027}\Bigg\} \\ & \div (1 - (0.98)[(-0.00667)e^{-34.129} + (0.98667)e^{-4.027}]) \\ & = 0.2332 \text{ day} \end{aligned}$$

Two-Moment Approximations

In many practical situations, it is easy to find the mean and variance of the interarrival times or of the service times. This information can be used to form a linear interpolation of a measure of interest using simpler models to get the measure of interest for a more complex situation. The squared coefficient of variation of the interarrival times c_a^2 and/or the service times c_s^2 are used as weights in the interpolation formula. The two-moment approximation is most useful when

$$0 \le c_a^2 \qquad c_s^2 \le 2$$

which covers most cases of interest in industrial applications.

The two-moment approximation method can even be used within an asymptotic approximation to ease the computational burden. The parameter evaluation formulas, Eq. (11.4.35) for d and Eq. (11.4.34) for γ, may be approximated by

$$\delta \approx \frac{\delta^{(d)}\delta^{(e)}}{(1 - c_s^2)\delta^{(e)} + c_s^2\delta^{(d)}} \tag{11.4.48}$$

and

$$\gamma \approx [\gamma^{(e)}]^q[\gamma^{(d)}]^{1-q} \tag{11.4.49}$$

where

$$q = \frac{c_s^2\delta}{\delta^{(e)}} \tag{11.4.50}$$

$$\gamma^{(e)} = \rho \tag{11.4.51}$$

and $\delta^{(e)}$ is given by Eq. (11.4.44), $\gamma^{(d)}$ is given by Eq. (11.4.47) and $\delta^{(d)}$ solves Eq. (11.4.46). Solving Eq. (11.4.44) is the only iterative element of this approximation and is solved much easier than the original Eqs. (11.4.35) and (11.4.34) for general $B(y)$.

Several results employing a two-moment approximation are now presented.

GI/G/1

$$P\{W_q > 0\} = \begin{cases} \rho + \dfrac{(C_a^2 - 1)\rho(1-\rho)(1 + C_a^2 + \rho C_s^2)}{1 + \rho(C_s^2 - 1) + \rho^2(4C_a^2 + C_s^2)} & \text{if } C_a^2 \le 1 \\[2ex] \rho + \dfrac{4(C_a^2 - 1)\rho^2(1-\rho)}{C_a^2 + \rho^2(4C_a^2 + C_s^2)} & \text{if } C_a^2 > 1 \end{cases} \tag{11.4.52}$$

$$W_q = \begin{cases} \dfrac{\rho E(s)}{2(1-\rho)}(C_a^2 + C_s^2)e^{\frac{-2(1-\rho)(1-C_a^2)^2}{3\rho(C_a^2 + C_s^2)}} & \text{if } C_a^2 \le 1 \\[2ex] \dfrac{\rho E(s)}{2(1-\rho)}(C_a^2 + C_s^2)e^{\frac{(-(1-\rho))(C_a^2 - 1)}{C_a^2 + 4C_s^2}} & \text{if } C_a^2 > 1 \end{cases} \tag{11.4.53}$$

for C_a^2 not too large and $P\{W_q > 0\}$ not too small.

M/G/1/k: Finite Work Buffer Capacity. This model will not accept any of the work associated with an arrival exceeding the buffer limit.

$p(k) =$ steady-state proportion of all arrivals turned away due to the work capacity limit being met or exceeded by the arrival

$$\approx \gamma e^{-\delta k} \text{ for large } k \tag{11.4.54}$$

Conversely,

$k(\nu) =$ work capacity limit (or buffer size) that results in a proportion ν of arrivals being turned away

$$\approx \frac{1}{\delta}\ln\frac{\gamma}{\nu} \qquad \text{for } \nu \le 10^{-3} \qquad \text{and any } \rho \qquad \text{or } \nu \le 0.01 \text{ and } \rho < 0.8 \tag{11.4.55}$$

where two-moment approximations for δ and γ are given by Eqs. (11.4.48) and (11.4.49), respectively.

Example. Housings arrive at a machine center for primary drilling and machining operations according to a Poisson process at a rate of 1.5 per hour. The arriving housings are of differing sizes with the amount of work (number of operations) that is to be done on them in proportion to their size. The number of operations per housing is a random variable with mean = 15 and variance = 25. The machine center can perform machining operations at a fairly constant rate of 30 per hour. How much space should be provided in the buffer such that the probability that an arriving housing cannot be accommodated is less than 1 percent?

The data suggests that $\lambda = 1.5$ housings/hour, $E(s) = 15$ machining operations/housing, and var(s) = 25. The service rate of the machining center is 30 operations/hour; thus, $\sigma = 30$ operations. The offered load to the center is $\rho = (1.5)(15)/30 = 0.75$. We use Eq. (11.4.55) to answer the question posed and must complete the following calculations by using Eq. (11.4.51):

$$\gamma^{(e)} = 0.75$$

and Eq. (11.4.44):

$$\delta^{(e)} = \frac{1 - 0.75}{15} = 0.01667$$

and solving Eq. (11.4.46):

$$\frac{1.5}{30}(e^{15\delta^{(d)}} - 1) - \delta^{(d)} = 0$$

for

$$\delta^{(d)} = 0.03668$$

Then use Eq. (11.4.47)

$$\gamma^{(d)} = \frac{1 - 0.75}{(0.03668)(15) - (1 - 0.75)} = 0.8328$$

Eq. (11.4.48):

$$\delta = \frac{(0.03668)(0.01667)}{(0.8889)(0.01667) + (0.1111)(0.03668)} = 0.03236$$

Eq. (11.4.50):

$$q = \frac{(0.1111)(0.03236)}{0.01667} = 0.2157$$

Eq. (11.4.49):

$$\gamma = (0.75)^{0.2157}(0.8328)^{0.7843} = 0.8142$$

Eq. (11.4.55):

$$K(0.01) = \frac{1}{0.03236} \ln\left[\frac{0.8142}{0.01}\right] = 135.9 \approx 136$$

Over the long run, if the number of operations associated with an arriving housing is independently sampled from the work size distribution, the expected number of housings that are present when an arriving housing is blocked is $K(\nu)/E(s) = 136/15 = 9.064$. Since space is to be allocated, the area of the largest housing that the machine center sees is multiplied by $10 > 9.064$ to ensure the 1 percent blocking criterion is met.

Parallel Server Approximations

When c identical parallel servers are added to the complexities already discussed for the single-server case, approximations must be relied upon heavily to provide useful results. Analytical results are very limited and for special cases only. Two assumptions are made with respect to the behavior of the queuing process at service completions.

1. At a service completion, if k are left behind in the system, $0 < k < c$, the system acts like an M/G/∞ queue for which there is a server for each customer in the system. For such a system, the time until the next service completion has a distribution given by the steady-state residual life distribution of renewal theory,

$$B_e(t) = \frac{1}{E(S)} \int_0^t [1 - B(x)]dx \qquad t \geq 0 \tag{11.4.56}$$

2. At a service completion, if $k \geq c$ are left behind, the system acts like an M/G/1 queue with the service rate equal to $c\mu$. Both assumptions are exact if service times are exponentially distributed. And both assumptions will be used in conjunction with asymptotic and two-moment approximation approaches to develop useful results for multiple server models.

***M/G/*c.** The analysis required to determine the steady-state system size probabilities at an arbitrary point in time is made much simpler by the two preceding parallel server assumptions. The defining equations for these probabilities that follow allow a recursive solution:

$$P_j = \begin{cases} \dfrac{(c\rho)^j}{j!} P_0 & 0 \leq j \leq c-1 \\ \lambda \alpha_{j-c} P_{c-1} + \lambda \displaystyle\sum_{k=c}^{j} \beta_{j-k} P_k & j \geq c \end{cases} \tag{11.4.57}$$

where

$$\rho = \frac{\lambda}{c\mu}$$

$$P_0 = \left[\sum_{k=0}^{c-1} \frac{(c\rho)^k}{k!} + \frac{(c\rho)^c}{c!(1-\rho)} \right]^{-1} \tag{11.4.58}$$

$$\alpha_n = \int_0^\infty [1 - B_e(t)]^{c-1} [1 - B(t)] e^{-\lambda t} \frac{(\lambda t)^n}{n!} dt \qquad n \geq 0 \tag{11.4.59}$$

$$\beta_n = \int_0^\infty [1 - B(ct)] e^{-\lambda t} \frac{(\lambda t)^n}{n!} dt \qquad n \geq 0 \tag{11.4.60}$$

In general, the integrations in Eqs. (11.4.59) and (11.4.60) need to be numerically evaluated using quadrature techniques. It should be noted that P_j for $j = 0, 1, \ldots, c-1$ are equal to the corresponding P_j for a M/M/c system and, as a result, the probability for a customer waiting for service is

$$P\{W_q > 0\} \approx \frac{(c\rho)^c}{c!(1-\rho)} \left[\sum_{k=0}^{c-1} \frac{(c\rho)^k}{k!} + \frac{(c\rho)^c}{c!(1-\rho)} \right]^{-1} \tag{11.4.61}$$

which is the well-known Erlang delay probability. Similarly, the expected number in the queue may be related to the corresponding measure of a M/M/c system

$$L_q = \left[(1-\rho)\gamma \frac{c}{E(s)} + \rho \frac{E(s^2)}{2E(s)^2} \right] L_q^{(e)} \tag{11.4.62}$$

where

$$L_q^{(e)} = \text{expected number in the queue in a M/M/}c\text{ system}$$

$$= \frac{(c\rho)^c \rho}{(1-\rho)^2 c!} P_0 \tag{11.4.63}$$

$$\gamma = \int_0^\infty [1 - B_e(t)]^c dt$$

$$\approx (1 - c_s^2) \frac{E(s)}{c+1} + c_s^2 \frac{E(s)}{c} \tag{11.4.64}$$

if $0 \leq c_s^2 \leq 2$ and P_0 is given by Eq. (11.4.58).

A two-moment approximation for L_q preferred when $c_s^2 > 1$ is

$$L_q = \frac{1}{2}(1 + c_s^2)\,\frac{2L_q^{(d)}\,L_q^{(e)}}{2a\,L_q^{(d)} + (1-a)L_q^{(e)}} \tag{11.4.65}$$

where

$$L_q^{(d)} = \frac{1}{2}\left[1 + (1-\rho)(c-1)\frac{\sqrt{4+5c}-2}{16\rho c}\right]L_q^{(e)} \tag{11.4.66}$$

$$a = \begin{cases} 1 & \text{if } c = 1 \\ \dfrac{1}{c-1}\left[\dfrac{E(s^2)}{\gamma E(s)} - c - 1\right] & \text{if } c > 1 \end{cases} \tag{11.4.67}$$

and $L_q^{(e)}$ and γ given by Eqs. (11.4.63) and (11.4.64), respectively. Little's formula can be used to find the expected waiting time in the queue.

The probability that a customer waits in the queue for a specified amount of time possesses the following asymptotic approximation:

$$P\{W_q > x\} = \frac{(1-\rho)P\{W_q > 0\}\int_0^\infty e^{\delta t}[1 - B_e(t)]^{c-1}[1 - B(t)]\,dt}{\rho s\int_0^\infty t e^{\delta t}[1 - B(ct)]\,dt}\,e^{-\delta x} \tag{11.4.68}$$

where δ is the positive solution of

$$\lambda\int_0^\infty e^{\delta y}[1 - B(cy)]\,dy = 1$$

and $P\{W_q > 0\}$ is given by Eq. (11.4.61). Equation (11.4.68) is most effective when

$$x \ge \frac{E(s)}{\sqrt{c}}$$

and

$$P\{W_q > 0\} \ge 0.2$$

M/G/c/N: Finite Capacity Queue. The steady-state system size probabilities p_j possess defining Eq. (11.4.57) with the addition of an equation for the capacity state,

$$P_N = \rho P_{c-1} - (1-\rho)\sum_{k=c}^{N-1} P_k \qquad j = N \tag{11.4.69}$$

Probabilities may be computed by finding $[P_j/P_0]$, iteratively, using Eqs. (11.4.57) and (11.4.69) and then finding P_0 by solving

$$\sum_{j=0}^{N}[P_j/P_0] = \frac{1}{P_0}$$

In turn, the probability of waiting in the queue for a time greater than t is found using

$$P\{W_q > t\} = \frac{1}{1-P_N}\sum_{j=c}^{N-1} \mathrm{P_j}\sum_{k=0}^{j-c} e^{-c\mu t}\frac{(c\mu t)^k}{k!} \qquad t \ge 0 \tag{11.4.70}$$

GI/G/c. Although attaining tractable results is a formidable challenge, a two-moment approximation for the expected waiting time in the queue provides good results for $0 \le c_a^2$,

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$c_s^2 \le 1$. The interpolation formula is the weighted harmonic mean of the expected waiting time in the queue for a M/M/c system, W_q(M/M/c), a M/D/c system, W_q(M/D/c), and a D/M/c system, W_q (D/M/c), and has the form

$$W_q \approx (C_a^2 + C_s^2)\left[\frac{1 - C_a^2}{W_q(\text{D/M/}c)} + \frac{1 - C_s^2}{W_q(\text{M/D/}c)} + \frac{2(C_a^2 + C_s^2 - 1)}{W_q(\text{M/M/}c)}\right]^{-1} \tag{11.4.71}$$

where

$$W_q(\text{M/M/}c) = \frac{(c\rho)^c}{c!c\mu(1-\rho)^2}\left[\sum_{k=0}^{c-1}\frac{(c\rho)^k}{k!} + \frac{(c\rho)^c}{c!(1-\rho)}\right]^{-1} \tag{11.4.72}$$

$$W_q(\text{M/D/}c) \approx \frac{1}{2}[1 + C(c,\rho)]W_q(\text{M/M/}c) \tag{11.4.73}$$

$$W_q(\text{D/M/}c) \approx \frac{1}{2}e^{-2(1-\rho)/3\rho}[1 - 4C(c,\rho)]W_q(\text{M/M/}c) \tag{11.4.74}$$

$$C(c,\rho) = (1-\rho)(c-1)\frac{\sqrt{4+5c} - 2}{16c\rho} \tag{11.4.75}$$

Example. A PC clone manufacturer offers a warranty service that allows buyers to send back their defective PCs for free repairs during the warranty period. Defective units arrive to the service area according to a Poisson process at a rate of 300 per month. Three technicians are on duty at all times and work independently but have a common service time distribution with $E(s) = 0.00667$ per month and Var $(s) = 0.0000578$. An analysis is required on how responsive the service facility is to customer needs.

The data suggests that $\lambda = 300$, $\rho = \lambda E(s)/c = (300)(0.00667)/3 = 0.667$, and $C_s^2 = \text{Var}\,(s)/E(s)^2 = 0.0000578/0.00667 = 1.3$. To estimate the expected number of units in the queue, calculations are required by using in turn Eq. (11.4.58):

$$P_0 = \left[1 + \frac{(3)(0.667)}{1} + \frac{[(3)(0.667)]^2}{2} + \frac{[(3)(0.667)]^3}{3!(1-0.667)}\right]^{-1} = 0.1111$$

(which is the proportion of time all technicians are idle), Eq. (11.4.64):

$$\gamma = (1 - 1.3)\left(\frac{1}{150(4)}\right) + 1.3\left(\frac{1}{150(3)}\right) = 0.0024$$

Eq. (11.4.63):

$$L_q^{(e)} = \frac{[(3)(0.667)]^3(0.667)}{3!(1-0.667)^2}(0.1111) = 0.8889$$

Eq. (11.4.67):

$$a = \frac{1}{2}\left[\frac{(0.0001)}{(0.0024)(0.00667)} - 3 - 1\right] \equiv 1.1395$$

Eq. (11.4.66):

$$L_q^{(d)} = \frac{1}{2}\left[1 + (1-0.667)(2)\frac{\sqrt{4 + (5)(3)} - 2}{(16)(0.667)(3)}\right](0.8889) = 0.4663$$

and, finally, using Eq. (11.4.65), we have the desired result:

$$L_q = \frac{1}{2}(1 + 1.3)\left[\frac{(2)(0.4663)(0.8889)}{(2)(1.1395)(0.4663) + (1 - 1.1395)(0.8889)}\right] = 1.0155 \text{ PCs}$$

Using Eq. (11.4.61), we find the following probability of an arriving PC waiting for a technician to become free:

$$P\{W_q > 0\} = \frac{[(3)(0.667)]^3}{3!(1 - 0.667)}(0.1111) = 0.4444$$

SUMMARY REMARKS

Queuing theory is essential in analyzing and evaluating bottleneck and congestion problems that are frequently encountered in the field of industrial engineering. Markov chain theory provides the analytical foundation for the methods presented in this chapter. For the more basic models, the events representing arrivals and services are independent and exponentially distributed. For more complicated situations where one or more of these features is absent, the approach is to impose conditions that will closely resemble a Markov structure in order to gain the analytical properties that can be used to approximate the system performance measures.

It is important to note that the models presented here are based on long-run equilibrium, (i.e., steady-state conditions, where time is not of concern). This provides information for understanding the systems under investigation and in making large-scale evaluations. The transient analysis of queues that involve dynamic conditions where time must be considered can be quite complex, and closed-form results for analyzing these systems are rare. Methods such as simulation and approximation algorithms are employed for these cases.

Practitioners must decide on the appropriateness of a model for the particular operational conditions relative to the uncertainty, risk, and variation in the processes. They must also consider the influence and impact of human behavior that is implicitly involved in most industrial engineering applications.

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CHAPTER 11.5

SIMULATION METHODOLOGY, TOOLS, AND APPLICATIONS

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Simulation methods of analysis, supported by increasingly powerful and user-friendly software tools, are gaining greater acceptance as an indispensable aid to business managers, engineers, and analysts seeking productivity improvements. This chapter provides an overview of simulation technology and its effective application to process improvement, enumerates and categorizes typical application areas amenable to simulation analysis, and provides case studies as examples.

INTRODUCTION

Simulation modeling and analysis, long the specialized province of mathematicians and computer science specialists, has entered the mainstream of methods available to help organizations (whether business, governmental, educational, or military) increase their efficiency and effectiveness. The proved abilities of simulation to attack a wide range of problems and investigations rest on its abilities to accommodate stochastic variation, analyze discrete or continuous variables, or both, and provide visualization via animation.

In this chapter we first enumerate the business motivations for using simulation technology. Next, we compare and contrast simulation worldviews, present an application-oriented simulation methodology, list application areas of simulation, and specify critical success factors. After reviewing available simulation tools, we discuss their integration with allied analytical methods and venture predictions on future trends.

BUSINESS MOTIVATIONS

There are many reasons why use of computer simulation has increased in popularity in the last 20 years. Some of these reasons are the reduction in cost of computers and simulation software, emergence of more user-friendly and powerful simulation software, increase in the speed of model building and delivery, and acceptance of an established set of guidelines of simulation model building (see the later sections, Critical Success Factors, and Overview of Tools Available). Other reasons for the increased popularity of simulation modeling stem from the expansion of global business, and are based on the following unique advantages that simulation provides to businesses.

Increase in Global Competition. In the last 20 years, pressures exerted on businesses to increase their competitiveness have intensified because almost all businesses can now provide products and services globally. During this time the more productive companies have significantly increased their market share. For example, in the automotive industry Toyota Motor Company has increased its share against less productive competitors such as General Motors Corporation. The ever increasing pressure for businesses to implement continuous productivity improvement, apply business process reengineering for major productivity gains, convert to lean manufacturing and lean supply chains, and find the best alternative system design and operation forces businesses to use computer simulation as a tool for testing the new conditions. Since the new systems that are being built are generally more complex and costly and have less room for error due to competitive pressures, the businesses have to rely more on simulation to build the most efficiently designed and operated systems. The new systems have to be optimized in their parameters right from their beginning rather than in several months, as has been observed in semiconductor and automotive manufacturing plants.

Cost Reduction Efforts. The last 20 years have also been the era of lean or agile systems, especially in manufacturing and supply chain systems. Companies are forced to increase their production rates and flexibility while reducing their investments in inventories, equipment, and labor. Companies with nimble systems and lower costs have much higher shareholder value in the business marketplace. Lean systems are also more prone to variations in the product demand, lead times, unscheduled downtimes, and quality levels. In design of such systems, simulation modeling becomes an essential tool to increase the robustness of the system relative to internal and external disturbances.

Improved Decision Making. The decisions that management makes under daily dynamic conditions not under management's direct control, or management decisions that are made relative to short-term and long-term changes planned for the system, may be suboptimal if simulation modeling is not used to test the effectiveness of each decision. Simulation modeling has been proved an effective tool in training managers because they can understand the effects of their decisions on the important performance metrics of the system. The cause-and-effect relationships observable through running of the simulation models increase the effectiveness of the decision makers. The best decisions under product mix changes, resource breakdowns, process and policy changes, schedule changes, priority changes, addition and deletion of resources, and maintenance policy changes are examples where management can gain significantly from simulation modeling.

Effective Problem Diagnosis. Problem-solving aids that help management solve problems such as throughput reduction, large setup times, imbalance in resource utilization, large inventories and waiting times point to simulation as the most effective tool. One can analyze the current system as well as the suggestions for improvement of the current system using simulation. The other analytical tools of operations research such as mathematical techniques, artificial intelligence, statistical techniques, and root cause analysis techniques either require too many simplistic assumptions to solve the problem or are too complex to be explained credibly to management. Simulation models, especially when coupled with their animation capabilities, can solve a problem at different levels of detail and complexity with the credibility management requires for effective use in real-life situations.

Prediction and Explanation Capabilities. Simulation modeling provides both prediction and explanation of a system's performance under different conditions. In addition to predicting what the system's performance will be for a set of conditions, the user can also comprehend the reasons why the system produces those results and behaves in a certain fashion through the user-defined simulated time period. Deeper understanding of the cause-and-effect relationships in the system also helps management formulate new or improved ideas to manage the system more effectively. In contrast to simulation modeling, other operations modeling tools are generally deficient in their explanatory capabilities and time-based evaluation of the system.

One can classify the usage of computer simulation in businesses as strategic, tactical, or operational based on the time horizon of the decisions made in the simulation study. In strategic uses, the time horizon of the decisions made in the study generally covers from three years to five or more years into the future and upper management of a company is the customer of such simulation studies. Simulation studies done for effective decision making in new product development, product portfolio management, or new plant and warehouse construction fit this category. In tactical uses of simulation, middle management is the customer of such simulation studies and the decisions made cover one to three years into the future. Typical examples of decisions made in such studies include the purchase of new machines and equipment pertinent to an existing facility, master scheduling for maximum efficiency of resources, adding a new shift to an existing facility, the addition and/or resizing of buffers, or logistics and supply chain studies. In operational uses of simulation, the time horizon of the decisions made in such studies can be in days to weeks and months up to one year into the future. The decisions made by lower-level management involving detailed scheduling of products, workforce assignments, overtime decisions, lot sizing, and setups are typical in such studies.

The simulation models built for strategic, tactical, and operational decisions require different levels of modeling detail, decision variables, verification and validation methods, and animation. For example, a strategic level model for new product portfolio management for a Fortune 100 company may include only the new product development projects whose cost exceeds $10 million; represent the hundreds of tasks in the product development process as 10 to 15 major tasks in the model; use the shareholder value, return on investment, cash flow, and cost of programs as the decision variables; and animate the system using dynamic time-based cost, return on investment, cash flow, and resource utilization diagrams. As a contrasting example, an operational level model for finding the optimal number of forklift trucks in a receiving and shipping department at a plant may include only those loads carried by the forklift trucks; represent the forklift truck movements with acceleration, deceleration, and maximum speed; use the truck loading and unloading times, the number of emergency deliveries due to starving stations, and the number and the utilization of the forklift trucks as the decision variables; and animate the system using dynamic icons representing the forklift trucks and the delivery trucks at the docks being loaded and unloaded, static icons representing the stations where the deliveries and pickups are made, and dynamically changing numbers showing the inventory status of each load at each station.

SIMULATION WORLDVIEWS

This section describes the three fundamentally different and contrasting simulation worldviews: discrete-event, continuous, and mixed [1]. It also provides a subsidiary classification for the discrete-event worldview.

The Discrete-Event Worldview

In this worldview, time progresses in a series of steps, and significant variables within the model are integer-valued. Therefore, the concept of derivative is inapplicable, since *discrete* in this sense is the antonym of *continuous.* The number of items in a queue, for example, is inherently integer-valued. The function L(*t*), specifying queue length as a function of time, is constant during intervals of time and changes value at arbitrary instants of time. Its derivative is zero on the intervals and undefined at the instants of change from one integer value to another; its integral is equal to the weighted average queue length. As another example, the status of a server may be considered binary (0 = idle, 1 = busy) or at least integer (0 = idle or starved, 1 = busy, 2 = blocked, 3 = not in service or "down"). In this worldview, differential or difference equations are inapplicable. The discrete-event worldview applies well to study of queuing systems—and a rich variety of simulation applications can and should be viewed as queuing systems. Figure 11.5.1 illustrates the behavior of a typical discrete variable as a function of simulated time.

The Activity-Oriented Approach. In the *activity*-oriented approach to discrete-event simulation modeling, the modeler develops characterizations of each significant activity within the system under study (see Fig. 11.5.2). These characterizations describe the system changes and quantify the passage of time during each activity (e.g., awaiting service, repairing a server, or receiving service). This orientation is most conveniently employed in the context of using a general-purpose programming language to write subroutines or functions driven by a simulation engine (see section, Overview of Tools Available). For example, the Receive_Service activity subroutine would update the busy time of the server and increment the cumulative number of items served by that server.

The Event-Oriented Approach. In the *event*-oriented approach to discrete-event simulation modeling, the modeler develops characterizations of each significant event within the system under study. Whereas activities span an interval of time, events occur at instants of time. This orientation, likewise, is most conveniently employed in the context of writing subroutines or functions to be called by a simulation engine. For example, the Completion_of_Service event subroutine, invoked at time t_0, would increment the cumulative number of items served by that server, and then examine $L(t_0)$: if $L(t_0) > 0$, decrement it by 1 and move one item from queue to server; else set server status to idle.

The Process-Oriented Approach. In the *process*-oriented approach to discrete-event simulation modeling, the modeler develops a characterization of how items (airplanes, customers, crankshafts, patients, mortgage applications, telephone inquiries, and so on) flow through the system under study. This orientation is most conveniently employed in the context of using either a computer language (for example, general-purpose system simulator [GPSS]) or a simulation package expressly designed for this use.

The Continuous Worldview

In this worldview, the system to be modeled is described in terms of differential and/or difference equations, exploiting the fact that variables of interest are continuous and differentiable

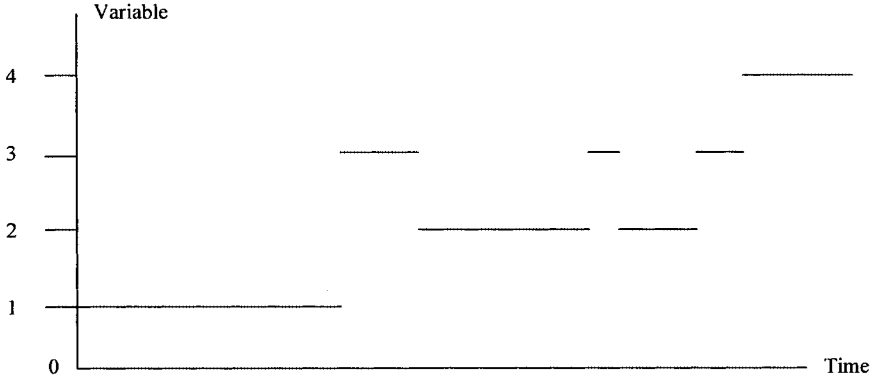
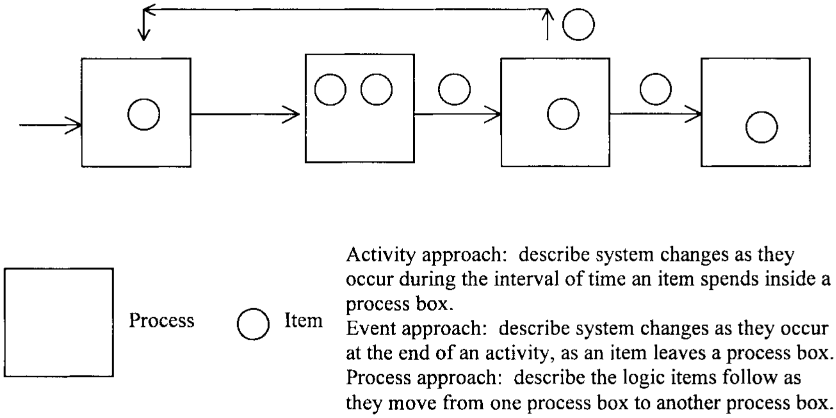


FIGURE 11.5.1 Graph of typical discrete variable as function of time.



Activity approach: describe system changes as they occur during the interval of time an item spends inside a process box.
Event approach: describe system changes as they occur at the end of an activity, as an item leaves a process box.
Process approach: describe the logic items follow as they move from one process box to another process box.

FIGURE 11.5.2 Comparison of activity, event, and process approaches.

functions of time. Such variables might be temperature, pressure, volume (e.g., of fluid in a tank), displacement, intensity of light, or diminution of strength. The analysis of the system then involves integration of these equations as time is driven forward. The continuous worldview is well suited for modeling of physical systems, as is regularly done in structural analysis (e.g., the compression or extension of a spring). The choice of this worldview or the discrete-event worldview may depend on the needs of the analyst. For example, consider a food-processing operation in which containers are filled with finely granulated sugar. The analyst may consider the state of the container as a discrete variable equal to 0 (container not full) or 1 (container full). Or, the analyst may consider the amount of sugar in the container as a continuous variable ranging from 0.0 (container empty) to 1.0 (container full). When using this worldview, the modeler often writes subroutines in a computer language such as FORTRAN or C to be driven by a simulation engine. The graph in Fig. 11.5.3 illustrates the behavior of a typical continuous variable as a function of simulated time.

The Mixed Worldview

As its name implies, this worldview conflates the discrete and continuous approaches. The modeler begins by describing the system in terms of differential or difference equations, and then specifies threshold values beyond which each equation is no longer applicable. Extend-

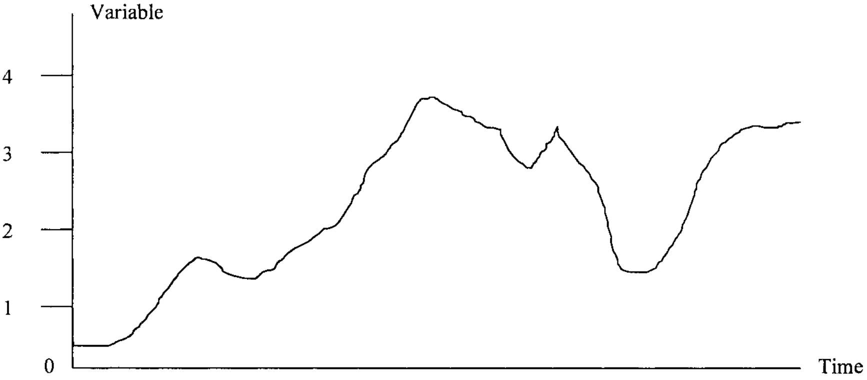


FIGURE 11.5.3 Graph of typical continuous variable as a function of time.

ing the previous example, the equation describing the extension of a spring as a function of time instantaneously ceases to apply when the threshold of elastic limit is crossed. The mixed worldview adapts well to modeling processes such as synthesis of chemicals or refining of oil, in which temperature, pressure, and concentration are continuous variables. Increase or decrease of these variables across thresholds may trigger events such as the startup or shutdown of a furnace, or the opening or closing of a valve. Hence, analysis should first consider the continuous aspects of the system, and then superimpose the discrete aspects, such as event triggers, on the continuous behavior. The analyst studying a system by using the mixed worldview may proceed as for the continuous worldview (writing subroutines and also specifying thresholds to be monitored by a simulation engine), or may use a simulation package expressly designed to include not only discrete and continuous modeling capabilities but also their interaction. For further descriptions of modeling tools available, see the later section on available tools. Figure 11.5.4 illustrates the interaction of a continuous variable crossing a threshold and a discrete variable as a function of simulated time

AN APPLICATION-ORIENTED SIMULATION METHODOLOGY

The application-oriented simulation methodology suggested here has eight phases:

Phase 1. Define the problem
Phase 2. Design the study
Phase 3. Design the conceptual model
Phase 4. Formulate inputs, assumptions, and process definition
Phase 5. Build, verify, and validate the simulation model
Phase 6. Experiment with the model and look for opportunities for design of experiments
Phase 7. Document and present results
Phase 8. Manage the model life cycle

Each phase is described by detailed steps in Table 11.5.1. Although these phases are generally applied in sequence, one may need to return to the previous phases due to changes in the scope and objectives of the study. In particular, phases 3 through 6 of the process may be repeated for each major alternative studied as part of the project.

It should be noted that the items listed for phase 5 and phase 7 are interpreted as guidelines rather than steps. In previous papers, Ülgen, Black, et al. [2,3] and Ülgen, Gunal, et al. [4] describe

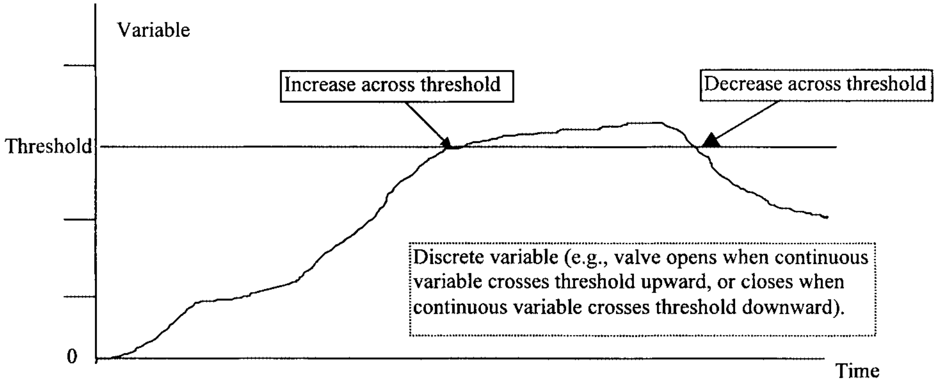


FIGURE 11.5.4 Graph of typical discrete and continuous variable interaction.

SIMULATION METHODOLOGY, TOOLS, AND APPLICATIONS

TABLE 11.5.1 Vital Questions at Various Phases of Simulation Projects

Project phase	Vital question
Define the problem	What will be studied, and for what business reason?
Design the study	What model(s) will provide what answers, and to whom?
Design the conceptual model	What modeling strategy (continuous, discrete, or mixed) will be used, and at what level of detail?
Formulate inputs, assumptions, and process definition	On what assumptions will the study be based, and what inputs and process definition will drive the model?
Build, verify, and validate model	Is the model built correctly (verification)? Is the correct model built (validation)?
Experiment with the model	What advice is available to us from the model?
Document and present results	What valuable experience is a foundation for further work?
Define the model life cycle	Can the model provide long-term benefits in any or all of training, scheduling, system redesign, and system launch?

each of these steps in detail. In a subsequent section on critical success factors, we discuss the role of some of these steps in successful execution of a simulation project.

TYPES OF APPLICATIONS

Simulation modeling has been applied in a large number of industries in solving problems in the strategic, tactical, and operational levels of management. Table 11.5.2 lists 12 major application areas of simulation modeling with samples of issues that correspond to the different levels of management. In general, discrete-event modeling has been the most commonly applied worldview for simulation applications. It has dominated all the application areas except the environmental and ecological system applications; the continuous worldview is a better fit for this domain. The combined simulation worldview has been the least applied worldview due to the complexity of building models with this approach. In many cases, simulation analysts (and some of the simulation software) have preferred to make assumptions to convert the continuous component of a model to its discrete equivalent. However, this simplification can have disastrous effects on the validity of the simulation for some systems with nonlinear model components.

The first three application areas of simulation, namely, manufacturing, material handling, and warehousing and distribution systems, have been the most popular ones among simulation applications if one looks at the published material to date. In the remainder of this section we will review the applications in these areas.

Applications in Manufacturing, Material Handling, and Warehousing and Distribution Systems

The simulation applications in these three areas can further be classified into four categories based on the development stage of the design of the system in question [5]. The four categories observed in this classification are applications that belong to the (1) conceptual design phase, (2) detailed design phase, (3) launching phase, or (4) fully operational phase of the system. The *conceptual design phase* refers to the initial stage when the new methods of manufacturing, material handling, warehousing and distribution are tested by management. Discrete-event simulation packages with 3D animation capabilities are the popular simulation tools at this phase. During the *detailed design phase* detailed layout plans and equipment specifications are verified for the system. The principal factors considered here include equipment justifications (e.g., the number of hold tables, power and free carriers, the size of buffers), cycle time verifications (e.g., conveyor speeds, line throughput), and line operational and scheduling issues (e.g., logic for evacuating ovens and paint booths, repairs, and product mix decisions). Discrete-event simulation packages

TABLE 11.5.2 Simulation Application Areas

Type of system	Management level	Typical issues
Manufacturing systems	Strategic	Plant design and layout
	Tactical	Purchase of new machine
	Operational	Scheduling and control
Material-handling systems	Strategic	Using conveyors or AGVs in assembly plants
	Tactical	Capacity and number of AGVs
	Operational	Route assignment to forklift trucks
Warehousing and distribution systems	Strategic	Warehouse location, capacity, and layout
	Tactical	Dedicated versus random storage
	Operational	Order pickup sequencing
Transportation and logistics systems	Strategic	Selection of hubs and geographic markets for an airline
	Tactical	Number and capacities of airplanes
	Operational	Plane scheduling and routing
Health systems	Strategic	Number of hospitals and clinics in a geographic area
	Tactical	New equipment for a clinic
	Operational	Nurse and technician staffing in an emergency room
Public systems offices	Strategic	Location of Social Security offices
	Tactical	Flow of civil lawsuits
	Operational	Manpower planning and scheduling
Military systems	Strategic	Defense system design and operation
	Tactical	Airlift system design and operation
	Operational	Airplane maintenance scheduling
Computer systems	Strategic	E-commerce system design and operation
	Tactical	Local area network (LAN) design and protocol selection
	Operational	Dynamic priority assignment for jobs in the memory queue
Communication systems	Strategic	Network design
	Tactical	Client/server system design
	Operational	Switch buffer management
Project planning and control	Strategic	New product portfolio management
	Tactical	Dynamic resource reallocation to projects
	Operational	Overlapping project activities and activity crashing
Environmental and ecological systems	Strategic	Pollution control policies for a city
	Tactical	Flood control policies
	Operational	Paint shop scheduling for minimizing pollution
Financial planning	Strategic	Capital investment decisions
	Tactical	Buy or make decisions
	Operational	Cash flow management policies

with built-in detailed equipment features and 3D animation features appear to be the most popular packages used at this stage. The *launching phase* refers to the stage when the plant operates below the designed operational conditions. In some cases it may take up to six months for the plant to operate under maximum-capacity conditions. Simulation studies performed at this stage are generally used to test operational policies (e.g., operate one of the two paint booths at a time, run each shop for one-half of the total available time, use different product mixes). Discrete-event simulation packages used at this stage do not typically require the detailed equipment features or the 3D animation features. The simulation program generators with user-friendly features are the most popular packages used at this phase, as models tend to be at a macro level rather than a micro level. The *fully operational phase* refers to the stage during which the plant is operating at its anticipated capacity. The simulation studies done at this phase consider product mix decisions, new product introductions, new operational policies, and line modifications. Simulation software used at this phase generally require the same capabilities as that used at the launching phase.

These simulation phases will be highlighted as we discuss three case studies [5] belonging to manufacturing, material handling, and warehousing and distribution application areas.

Case Study 1: Trim and Final Assembly Line Design. This simulation study was performed during the detailed design phase of a new conveyor system. An assembly plant would be making several different models of cars on one trim line. The process and flow of jobs in the system showed differences with respect to the model of cars. The conceptual design of the new system was completed following the previous version of the system. However, to accommodate the variety of the product assembly sequence, many new hardware pieces were needed. To ensure that the system could move the desired product quantities between various parts of the system, a detailed simulation model was built. An important parameter of the design was the mix of models in the target production rate. The objectives of the simulation study were to

- Verify the capability of the conveyor system to move the target number of vehicles through the trim system by considering various product mixes.
- Investigate various scenarios of assigning the size and location of empty carrier buffers by considering different product mixes.
- Analyze the impact of building a new buffer area to hold additional empty carriers.
- Determine the maximum allowable cycle times at several transfer stations by considering different product mixes.

Some of the important assumptions of the study were as follows:

- All manual operations can be completed within the given cycle time.
- All materials are always present.
- The line speed would be set higher than the required rate so that occasional downtimes could be tolerated.
- There are three models of cars and eight possible mixes of those models.

The system consisted of a chassis buildup system, an engine delivery system, a frame buildup system, and a final trim line. All material movement were made by using power and free conveyors except for the frame buildup area where a chain conveyor was used to move the units continuously. The transfer of units and subassemblies between major areas required complicated equipment that was prone to mechanical failure. Since there was limited room for buffers, an additional storage space was designed at the mezzanine level. The size of the buffer was being questioned since there were random downtimes at major transfer points. Since there were no detailed data, the system was designed to run at a speed 12 percent higher than the speed required, to allow time for breakdowns and shift breaks. However, the designers wanted to confirm that the system would be capable of delivering an average number of vehicles to meet the weekly production target at a 5 to 10 percent downtime rate. Based on past data, only an average recovery time of 5 min was specified. Also, the newly designed engine assembly area required the proper number of pallets in the system to support the production of all different types of jobs. Since there could be a variety of job mixes to be produced in the system, it was necessary to determine a number of pallets that would work with all possible product mixes. During the simulation study, first an evaluation of possible product mixes was made using a baseline layout. This portion of the study helped to determine the maximum allowable cycle times at critical stations to accommodate a variety of product mixes. Then the study focused on evaluation of the size of the empty carrier buffer. Three different layout alternatives were investigated. The simulation runs indicated that there would be no difference between layouts with respect to the average throughput capability. However, the utilization of various subsystems would be greatly affected by allocation of the empty carriers. Table 11.5.3 depicts, for all three layout alternatives, the time required to starve various subsystems after a catastrophic breakdown at one of the critical stations. The table clearly demonstrates that the first layout alternative is significantly better than the latter two in protecting the chassis buildup system against long periods of breakdowns.

TABLE 11.5.3 Time to Starve Subsystems After Breakdown

Subsystem	Layout 1 (min)	Layout 2 (min)	Layout 3 (min)
Chassis buildup 1 and 2	20.0	7.0	7.5
Chassis buildup 3	12.0	4.5	5.0
Chassis buildup 4	4.5	2.0	2.5

The model showed that at the transfer point from the engine build line to the engine deck area, the control logic and buffer size originally proposed would not support the cycle time requirement of the engine assembly area. Also, the simulation showed that the final assembly line would be starved immediately if the downtime at the body assembly area were longer than 3 min. It was also determined that the buffer storage space placed in the mezzanine level would be sufficient only for breakdowns of relatively short duration. An evaluation of an alternative design showed that additional empty carrier lanes were required to support the system for a longer time should downtime occur at a body assembly point.

Case Study 2: Paint Shop Material Handling and Model Mix Scheduling. This study involved simulation modeling and analysis of a paint shop and an adjoining automated storage and retrieval system (AS/RS) during the conceptual and detailed design phases. In addition to evaluating the design, the animation of the model was used as a visual tool to facilitate the brainstorming sessions of the design team. The objectives of this study were as follows:

During the conceptual design phase:

- Evaluate the conceptual design at each iteration of the design cycle to determine the potential bottlenecks and identify alternative solution strategies.

During the detailed design phase:

- Determine the throughput capability of the system.
- Assess the feasibility of the proposed shift schedules and paint booth strip sequences.
- Investigate the best stock levels of various products in the AS/RS.
- Analyze the impact of different trim line operation schedules on the number of out-of-sequence conditions.

The system consisted of the following subsystems in sequence: (1) electrocoat and phosphate, (2) sealer lines and sealer gel oven, (3) prime booth and prime oven, (4) main enamel booth and enamel oven, (5) inspection lines, (6) spot repair area, (7) second-coat paint booth and oven, (8) paper masking and repair lines, and (9) the AS/RS (see Fig. 11.5.5). The

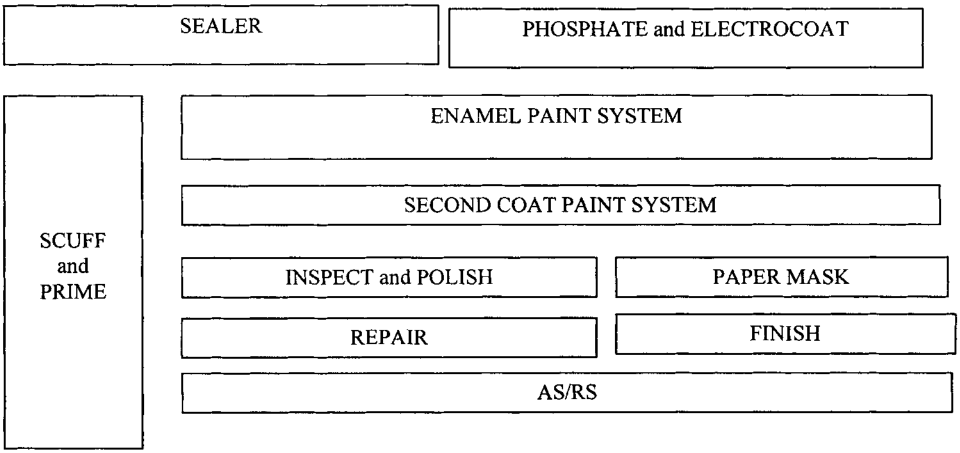


FIGURE 11.5.5 Layout of paint shop and adjoining automated storage and retrieval system.

material-handling equipment in the system consisted of many two- and three-strand chain conveyors, lift tables, turntables, and power roll beds.

The following parameters and variables (evaluated in what-if scenarios) were used in the simulation model: (1) conveyor speeds, spacing, and speedup section data, (2) cycle times at repair and mask lines, (3) cycle times at spot repair area, (4) product and paint mixes, and (5) major and minor repair percentages.

The model also required a front-end scheduling routine that was customized using a programming language (e.g., FORTRAN or C). Because some of the units required several passes through paint booths, they took a longer time to be ready for delivery to the trim lines. However, since the product mix showed significant differences between shifts, and since the trim lines operated on a different shift pattern, the jobs that required long processing times were pulled ahead of their original sequence. Thus, even though they would be taking more time than the other jobs, by the time they were completed, they would be able to catch their original position in the assembly sequence. Because of the randomness of the defect rate, there would be a good chance that some units would miss their sequence if they were not moved sufficiently ahead in the paint sequence. On the contrary, if they were moved too much ahead of their sequence, they would finish the paint process much earlier than the rest of the units. Therefore, to protect against such random variations in the makespan of different job types, a buffer storage bank was held in the adjoining AS/RS. This buffer would be sized to allow sufficient time for all units to catch their original sequence. The following are some of the original rules for resequencing the jobs:

- Jobs with two colors were moved ahead by 100 jobs for two product types.
- Jobs with three colors were moved ahead by 200 jobs for only one of the models.
- Pattern-color jobs were moved ahead by 200 jobs.
- A job with more than one matching criterion was moved ahead by the sum of the jobs required by each criterion (e.g., a two-color job with patterns was moved ahead by 400 jobs).

Some of the model assumptions were as follows:

- Two vehicle models, A and B, were considered. Model A vehicles have up to two coats of paint, whereas model B vehicles have up to three coats of paint.
- The model mix was known and assumed constant within a day.
- The major repair percentage is 22 percent and the minor repair percentage is 9 percent on average with random occurrences.

- Minor repair times are randomly distributed between 30 and 120 min and are performed at a dedicated area. Major repairs go through the second paint loop as necessary.
- Shift patterns are known and constant. The first shift is dedicated to model B and the second shift is dedicated to model A at the paint shop. The trim shop runs only one shift and makes both products.
- All conveyors run at full speed with negligible downtimes.

Analysis of the model involved an evaluation of the alternative job sequencing policies to choose one that will eliminate late jobs at the trim lines for all job types. In addition to sequencing concerns, the model was used to investigate the selectivity system (AS/RS) utilization. The runs of the model indicated that there was no reason to resequence model B vehicles since the plant was planning to store a full day's worth of buffer in the AS/RS for this type. The model showed that during the second shift in the paint shop all of the longest paint jobs would be completed for the next day's production at the trim lines. Results from some of the scenarios investigated are summarized in Table 11.5.4 for model A only. The table depicts the results with and without resequencing. In either case, different levels of model A buffer in AS/RS were tested to find a level that will balance the buffer size and the number of missed jobs. The results in the table indicate that a buffer size of 180 vehicles would be sufficient to avoid the missing jobs for the vehicle model A. It was also determined that with chosen buffer sizes, the utilization of the AS/RS was at a feasible level. The plant would make substantial cost savings by avoiding the reprogramming of their production monitoring system for vehicle model B.

TABLE 11.5.4 Results of Investigation

	Total missed jobs in a week			
	With resequencing		Without resequencing	
Model A buffer	Single coat	Double coat	Single coat	Double coat
135	120.32	16.29	0	115.76
160	14.75	4.43		56.45
170	1.09	4.21	0	40.32
180	0	0	0	30.20
200	0	0	0	12.29

Case Study 3: Warehousing Study. This project studied the proposed changes to a warehouse and the proposed material-handling equipment. The modifications to the system were needed as a result of increased storage, shipping, and receiving volumes anticipated due to packaging changes in existing products and introduction of new product lines. It was desired to determine alternative ways of increasing both cubic storage space and material-handling (shipping and receiving) capabilities. The challenge was to optimize the layout of the warehouse and select the most suitable material-handling equipment to provide adequate service based on planned future volumes.

The goals of the study were to identify system constraints that could limit future space and handling requirements and to suggest potential improvements and modifications to the system design. The design alternatives were based on the following system parameters: (1) dedicated versus random storage rules, (2) original rack orientation versus rotated (perpendicular to the docks) orientation, (3) aisle width and overall storage space utilization, and (4) capacity of material-handling equipment—most notably the number of lift trucks.

The results from the simulation model demonstrated that (1) randomized storage was better suited to this situation than dedicated storage, (2) the rotated orientation with the corresponding narrower aisle configuration resulted in an 85.96 percent increase in overall unit load storage capacity, (3) the rotated orientation also resulted in an increase from 23.57 to

41.95 percent in total storage space utilization, and (4) the existing number of lift trucks was sufficient to service the increased volumes.

CRITICAL SUCCESS FACTORS

The proper introduction of simulation into a company or business unit within a company begins by gaining management understanding and support, not by training at a technical level. Managers not already acquainted with simulation should first be reminded of the business motivations for using it and then provided with an overview of how simulation works, what it can accomplish when properly used, what its limitations are, and the type and scope of investment required as a prerequisite to obtaining benefits from simulation. Serious errors to avoid are overselling the benefits or understating the investments in personnel, training, time, data collection, and software required to obtain those benefits. Valuable resources for the introduction of this technology are benchmarks of companies using simulation, overview seminars, attendance at simulation conferences that provide nontechnical tutorial tracks, and nontechnical books on simulation such as Refs. [6, 7]. After tentative acceptance of simulation—that is, a willingness to "try it out" or "give it a test drive"—has been achieved, an initial simulation project should be specified and staffed. Very importantly, this project should be *small* and of sharply defined scope and objectives so that managers will be able to recognize success when it has been achieved. As examples (compared with the types of applications in the previous section), simulate one work cell, not one production department; simulate one restaurant, not all six in the city; simulate one baggage claim area, not the whole airport terminal; simulate one ward, not the fifth floor of the hospital.

When staffing a simulation project, industrial engineers are the simulation champions of choice, due to their experience in assuming a holistic process viewpoint, training in simulation—hence awareness of its capabilities and limitations, knowledge of mathematics and statistics, and extensive experience serving as a communication conduit between managers and production workers and their supervisors. Successful simulation requires a suite of skills in addition to model building: statistical analysis, oral and written communication, interpersonal diplomacy, and, most fundamental, a thorough understanding of the current or proposed production system to be modeled and analyzed. Particularly when a company is beginning to use simulation, the model-building skill and system understanding are likely to repose in two different people, underscoring the importance of communication skills on the part of the model-builder/simulation analyst. The simulation analyst must be able to enlist the process expert's cooperation while developing understanding of the process, gathering data, and later presenting results and recommendations emerging from the study.

When the first success of simulation whets managers' appetites for further use of simulation, these managers should establish a project discipline. A "road-tested" template for this discipline comprises eight phases (discussed in a previous section). Notice that much up-front work is necessary before actual modeling begins. As the project discipline indicates, by the time model construction begins, answers to many questions have been determined. Several of these questions and example answers are

- Question: What system is to be modeled?

  Example answer: Department B will be included in the model; upstream department A and downstream departments C and D will not be included in the model.

  Example answer: Departments B and C will be included in the model; upstream department A and downstream department D will not be included in the model.

- Question: What answers will the model provide?

  Example answer: The model will predict the maximum number of jobs per hour attainable by adjusting buffer sizes while leaving conveyor speeds unchanged.

Example answer: The model will specify the maximum number of jobs per hour attainable by adjusting conveyor speeds while leaving buffer sizes unchanged.

- Question: What modeling strategies will be used?

  Example answer: The frequent supply of raw material in small batches to a department will be treated as a continuous stream.

  Example answer: The five machining steps of Operation 30 will be treated as one process, not subdivided.

- Question: On what assumptions will the study be based?

  Example answer: If a given piece of equipment breaks down, repair can always begin at once.

  Example answer: Supply of raw material will never be exhausted.

To the uninitiated, model construction, very probably using unfamiliar software, seems the most daunting and time-consuming step. Veterans of simulation studies are well aware that data collection usually requires considerably more time. Verification of the model is akin to debugging—confirming that the model functions as the modeler intends. Validation of the model confirms that the model is an accurate representation of the current or proposed system relative to all performance metrics to be assessed by management (see Fig. 11.5.6).

Experimentation with the model, to learn more about the system under study, deserves a generous allotment of time; it is during this step that management receives a return on the investment in training, software, and time required to gather data and to build, verify, and validate the model. Statistical expertise is most essential during data collection (to incorporate statistically valid characterizations of stochastic data within the model) and during experimentation and analysis (to assess performance of candidate systems). Simulation studies, like any scientific inquiry, raise questions as well as answer them—after all, industrial engineers seek not just improvement, but *continuous* improvement! Therefore, documentation, both internal to the model and external (reports, project logbooks), is vital to enabling subsequent analyses to build on the work already accomplished instead of redoing it.

More administratively and strategically, managers should anticipate the problem of how to accommodate additional demand for simulation spawned by its initial success (a good problem to have). Will this demand be met internally or externally? Meeting it internally entails the assemblage of a staff of experts, by hiring them and/or providing appropriate training to current personnel. Meeting it externally requires establishment of a long-term, high-trust rela-

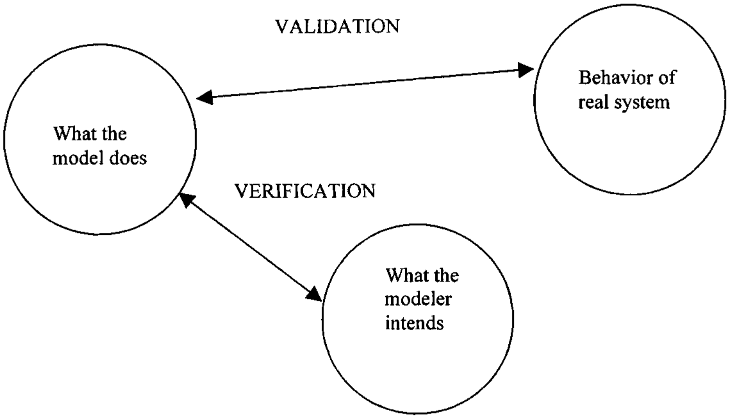


FIGURE 11.5.6 Relationship between model verification and validation.

tionship with a qualified vendor of simulation and analysis service. Training in-house process experts (e.g., production supervisors) to use simulation has the strong appeal of making the process expert and the simulation model builder one and the same—surely easing and enhancing the communication between them. In-house seminars and the establishment of an intracompany simulation users' group work well not only to publicize simulation as a value-adding technology, but also to disseminate knowledge of its proper praxis. Therefore, the initial simulation analysts should gradually migrate from the role of constructing models to order to the role of enabling colleagues to construct and analyze models. Recent advances in the intuitive usability of simulation tools (see the following section) have increased the plausibility of this choice. Even then, a relationship with a qualified vendor of simulation service should be on standby to handle urgent needs. This vendor should be a disinterested specialist in simulation modeling and analysis, not a vendor of production equipment or systems—the latter choice is akin to assigning a cat the guardianship of a canary.

OVERVIEW OF TOOLS AVAILABLE

The extensive array of analytical tools available for simulation analyses can conveniently, although imprecisely, be grouped into four categories: general-purpose languages, simulation languages, simulation packages (simulators), and tool suites. Table 11.5.5 lists the software that can be categorized into these four classes. More information on each software tool can be found in the *Proceedings of the Winter Simulation Conference,* published annually by a consortium of technical societies including the Institute of Industrial Engineers.

General-purpose programming languages amenable to mathematical expression, such as FORTRAN and C, have long been used for simulation. Using these languages, an expert can describe extremely complex, idiosyncratic systems to whatever level of detail may be appropriate relative to study objectives and the time and budget available. The use of a general-purpose language becomes much more efficient and effective when a simulation engine is available for tasks common to all simulations, such as maintenance of the simulation clock and of calendars of current and scheduled events within the model. In this situation, the analyst writes subroutines or functions that the simulation engine calls at appropriate times.

Other programming languages have been developed expressly for simulation modeling. Two of the most venerable and most widely known are GPSS (General Purpose System Simulator) and SIMSCRIPT. GPSS supports discrete-event simulation, but does not support the continuous or the mixed worldviews. Since GPSS is a block-structured language, whose blocks represent processes such as joining a queue, beginning to use a resource, or freeing a resource, it is

TABLE 11.5.5 A Classification of Simulation Software Tools

General-purpose software	C, FORTRAN, C++, Java
Simulation languages	GPSS/H, SLX, SIMSCRIPT II.5, AweSim, ModSim, Simple++, Extend, SIMAN/ARENA
Simulators	
Manufacturing	AutoMod, ProModel, WITNESS, Taylor II, Factor/Aim, ARENA, SIMUL8, Extend + Manufacturing, Quest
BPR	ARIS, ProcessModel, BP$im, SimProcess, Time Machine, Extend + BPR
Health systems	MedModel
Tool suites	Quest+IGRIP+Ergo RobCAD+RobMan+Simple++ ProModel+SimRunner+Stat::Fit AutoMod+AutoStat ARENA+OptQuest

particularly well suited to the process approach. SIMSCRIPT, a more complex and powerful language, supports the discrete, continuous, and mixed worldviews, partly because the elements of SIMSCRIPT are less explicitly linked to real-world elements than are those of GPSS.

Simulation languages are being rapidly and largely supplanted by simulation packages. Use of these packages greatly reduces (but does not eliminate) the writing of computer code. When using a simulation package, the user builds the model primarily with the mouse, using predefined constructs such as "machine," "resource," "conveyor," or "buffer." Process logic is then provided to the model via an English-like programming language, as shown in this generic example:

```
IF Utilization (resource_1)< Utilization (resource_2)
  THEN USE resource_1 for 2.5 min
  ELSE USE resource_2 for 3.5 min
END IF
```

Use of a simulation package shortens the model building, verification, and validation phase (the fifth phase in the project discipline recommended previously). Furthermore, use of a simulation package instead of a simulation language typically permits concurrent construction of a model and its animation.

Currently, simulation packages are evolving and coalescing into tool suites. For example, many simulation packages now include statistical capabilities to fit probability densities to empirical data, construct confidence intervals for system performance metrics, and undertake design-of-experiments calculations. High-quality packages readily interface with spreadsheets and database software. A worthy conceptual goal to be kept in mind by the analyst when choosing software tools is "Will I ever have to read an output number from one software tool so I can key it into another software tool as input?" Surely the desired answer to this question is "No"!

INTEGRATION WITH RELATED ANALYTICAL METHODS AND TOOLS

During the last 10 years, there had been significant progress in the integration of simulation tools with other analytical tools. Table 11.5.6 lists some of the software suites and suite components. The most significant among these has been the integration of discrete-event simulation tools with the ergonomics and robotics simulation tools that are based on the continuous simulation worldview. The toolset of Quest+IGRIP+Ergo by Deneb Corporation is one such example. The simulation analyst can develop a discrete-event model in Quest that may incorporate a robotic cell model developed in IGRIP as well as an ergonomic model of a human operating an assembly machine developed in Ergo. Many tool sets are tightly coupled while others can be combined with other software relatively easily. One such tool set component is the Optquest optimization software, which couples with a number of simulation software tools such as ARENA and WITNESS. On the other hand, the statistical input analyzers such as ExpertFit and Stat::Fit can easily be used by any simulation software since they need not be tightly coupled with them.

Simulation engines also have been used in scheduling software for many years in its deterministic form. Scheduling software such as AutoSched and Tempo perform their forward scheduling plans based on deterministic scheduling of events into the future. A more recent use of the simulation engines has been in the business process reengineering (BPR) tools. For

TABLE 11.5.6 Simulation Tool Suite Components

Optimizers	AutoStat, OptQuest, Optimizer, SimRunner
Animators	Proof Animation
Input data analyzers	ExpertFit, Stat::Fit, BestFit
Ergonomic analyzers	RobMan, Ergo
Robotic simulators	IGRIP, RobCad, SILMA, Workspace
Layout analyzers	FactoryFlow, LayOPT

example, ARIS, a BPR tool, incorporates a simulation engine to compare the performance of the current and future processes before new processes are implemented in a system.

FUTURE TRENDS

Simulation software tools will continue their integration with other tools to form tool suites. These other tools may be spreadsheets, statistical analysis software, mathematical optimizers, programmable logic designers, ergonomic analysis software, or process flow layout and analysis tools. Increasing understanding and prevalence of object-oriented software design and programming methods significantly assists the integration of traditionally freestanding simulation tools with these correlative analytical tools.

Spurred in large measure by the increasing power and ease of use of simulation tools, simulation is achieving not only more frequent use, but more widely based use. A few years ago, simulation studies were the province of highly specialized experts in simulation-specific computer languages; therefore, these studies were reserved for special occasions. Whereas work was brought from its place of origin to mainframe computers, personal computers and their software readily go where the work is. Simulation analysis will continue to follow this path. Increasingly, a simulation study will routinely be spawned by capital expenditure proposals, anticipated change in demand mix, suggestions of change in operational policy, or challenges to scheduling methods. As simulation increases its penetration within organizations, the simulation model builders will increasingly be the end users of the simulation results.

Also, the use of Internet-based (Web-based) simulation will increase, especially for large, complex models. Web-based simulation is highly attractive for such models, which characteristically make heavy demands on computer resources. Expert modelers can subdivide process logic within such models to enable multiple processors to undertake computational work concurrently. After that subdivision has been verified to be logically correct, the Internet provides an infrastructure for distributed processing.

Another significant trend in simulation is its increased use all along supply chains, in contrast to use within one company at a time. A supply chain, like any other chain, is no stronger than its weakest link. The benefits of long-term trust-based relationships with suppliers and vendors, compared to short-term price-based relationships, are rapidly becoming more conspicuous and more widely understood. Furthermore, it is no longer economically or operationally feasible to hide potential problems under a thick layer of inventory. Both these trends, in concert with the increasing ease of use of simulation software, will continue to increase the number of simulation studies whose scope extends far beyond the walls of one company.

The previous trend is one of several reasons that simulation is being applied to the analysis of larger and more complex systems. Increased use of parallel and distributed simulation, made possible by both hardware and software advances, will meet the escalating demands for computational power made by these large, complex simulation models.

SUMMARY AND CONCLUSIONS

Simulation analysis methods have high power and value, in the sense of business justification. The applicability of simulation, using an appropriate worldview, is extremely broad. Successful use of simulation is contingent on its proper introduction into a company, the establishment of and adherence to a well-defined and disciplined methodology, and the selection and proper usage of appropriate software tools. Furthermore, simulation analyses are capable of working synergistically with other analytical methods toward goals of process improvements and increased efficiency.

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BIOGRAPHIES

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Source: MAYNARD'S INDUSTRIAL ENGINEERING HANDBOOK

CHAPTER 11.6

CASE STUDY: NEURAL NETWORK APPLICATIONS

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A neural network approach to linking manufacturing parameters to an observable output (part thickness) is explored in this case study. The application involves a hypothetical setting in which part thickness is affected by several parameters; no known theoretical model exists to satisfactorily link the input parameters to thickness, and conventional linear regression does not offer satisfactory results. Because of its omnipresence and documentation in the neural network literature, backpropagation is chosen as the neural network architecture. The case also discusses how to use the empirical model yielded by the backpropagation network in an optimization strategy to determine parameter settings.

INTRODUCTION

Neural networks have recently become more widely used in industry and may provide a useful alternative for some IE applications. Drawing their inspiration from the hardware of the brain (i.e., the nervous system), these techniques represent an alternative approach to artificial intelligence (AI). The conventional approach to AI, which uses expert systems based on the software of the brain (the mind), is complemented by neural networks. The ideas behind neural networks are actually older than those behind expert systems. Their rediscovery in the 1980s was due to advances made by and recognized by a small group of researchers. This case study will briefly describe what neural networks are and how they may be applied using an illustration from a manufacturing quality setting. We will conclude with a discussion of their benefits and summarize the conditions that should exist for a neural network approach to be useful.

Description of Neural Networks

Neural networks are computational models based loosely on the hypothesized workings of the brain. While a variety of different models exist with varying applications, we will focus on neural networks for the task of empirical modeling, which uses sample data to build a model relating several inputs to one or more outputs [1]. Such neural networks prove useful when data exists or can be obtained cheaply, and when the underlying relationship is not well understood. For example, neural networks have been applied with increasing success to problems in the financial sector, where historical data exists in great quantities at no cost to the user. Examples of their application range from classifying a new venture as a "winner" or "loser" in terms of its predicted long-run operating performance, to predicting excess returns on large stocks, and determining the risk level posed by a loan applicant.

In contrast to expert systems, which implement rules extracted from an expert in order to use logic to solve a problem, neural networks learn by example. They build on the notion that for many, although not all, tasks human beings learn associations between inputs and outputs by way of numerous examples. Often, in these cases, articulating the actual rules for making these associations is difficult. For example, consider how children learn about animals, such as dogs. Rarely are they taught explicit rules to follow in order to identify an animal as a dog—such rules would quickly become too numerous and riddled with exceptions. Rather, with the help of numerous exposures to dogs of various breeds, shapes, and sizes, they become experts at dog identification. They are even able to generalize—to recognize as a dog an animal never seen before. The repeated exposure to examples experienced by humans led to the notion of statistical learning in neural networks.

Backpropagation Description

Although a wide variety of neural network approaches to empirical modeling exist, we will focus on the application of backpropagation in our case. Backpropagation is one algorithm for teaching a neural network to correctly associate inputs with outputs [2,3]. We choose this model not because it represents the very latest in neural network advances, but because it is widely available and applied [4], many rules of thumb for using it have become established, and many alternative models build on backpropagation and face some or all of the same application issues. All empirical modeling neural networks generate an output in response to a set of inputs, called input patterns. For example, in the case of risk classification, the input patterns may consist of several attributes of a loan applicant (salary, debt, years at current residence, etc.) and the output may consist of a classification such as "good" or "bad" risk.

Figure 11.6.1 shows a typical backpropagation neural network, with three layers of units: input, hidden, and output. These units transmit associated signals along the connections. Connections exist between units at adjacent layers and each connection has an associated weight that multiplies the signal traveling on it. Input units receive and transmit input pattern data. Output units give the final response of the neural network to the input pattern. Hidden units perform nonlinear transformations that play a key role in enabling the neural network to form nonlinear models. The output of a unit is called its *activation.*

A backpropagation neural network uses data to find the values of its unknown variables—the weights on connections in the network. The process of changing weights in response to repeated presentations of data is called *training.*

Computation of the final output of the neural network (the output node's activation) occurs in L stages, where L represents the number of layers (a backpropagation neural net-

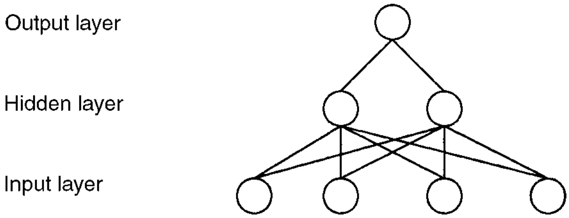

FIGURE 11.6.1 A neural network with one hidden layer.

work may have one or two hidden layers). Input units receive and transmit as output a vector representing a combination of input values to be associated with a desired output value. Hidden layer units compute their activations using the weighted signals from the previous (input) layer and a nonlinear transfer function—typically a sigmoid function that returns values within an interval such as (0,1). The neural network requires nonlinear transfer functions at the hidden layers in order to form empirical models that map nonlinear relationships. Otherwise, the neural network merely performs first-order linear regression.

Output layer units then use functions (possibly different from those at the hidden layer, e.g., linear) to compute their activation values, which represent the output of the entire network. The learning rule typically compares this final output value to the desired output value for the initial set of inputs during training of the network. Training consists of many cycles of presentations of a set of data: the training data. Early in training the actual and desired output values will likely differ significantly, but as weights adjust appropriately the difference—or error—decreases. In backpropagation, the learning rule attempts to adjust weights so as to minimize sum squared error (SSE) between actual and desired output values in the training set. Table 11.6.1 defines several error terms used including SSE. After training ends, a separate test set is used to assess performance and especially generalization: the ability of the network to give appropriate responses to new data.

Selection of the number of hidden units can pose a formidable challenge. Each hidden unit added to the network adds $(I + O)$ connection weights, where I = number of input units and O = number of output units. Various rules of thumb exist, but in essence, a delicate balance is usually sought. Too many hidden units, and hence too many weights, can lead to overtraining (akin to the statistical problem of overfitting): superior performance on the training set of data but poor generalization to new data (test data). Too few hidden units can prevent success on both training and test sets. As we will later see, the number of hidden units together with the number of data points in the training set and the length of the training period (number of cycles through the training data set) contribute to network learning and can affect overtraining. References [2,3,5] provide more details on neural networks in general and backpropagation in particular.

Differences Between Neural Networks and Linear Regression

Linear regression requires the analyst to assume a functional form of the model relating a set of inputs to one or more outputs, then to fit the available data to that model, which must be linear in the unknown parameters. For example, a linear first-order regression model, very commonly used, assumes the form

$$y = a_1x_1 + a_2x_2 + \cdots + a_nx_n + b$$

while another linear, higher order model might assume the form

$$y = a_1x_1 + a_2x_1x_2 + a_3x_2^3 + b$$

TABLE 11.6.1 Definitions of Error Terms

Term	Definition	Formula	Explanation
SSE	Sum of squared errors	$\sum_j (y_j - y_j^e)^2$	$j = 1,\ldots,N$ where N = number of data points, y_j = desired output for data point j, and y_j^e = output for data point j estimated by model.
RMS	Root mean squared error	Sqrt(SSE/N)	Square root of mean squared error.
TSS	Total sum of squares	$(N - 1)\sigma^2$	Where σ^2 is the variance of the data.
R^2	Coefficient of determination	1 – (SSE/TSS)	Used to assess model performance for a given set of data (near 0 means no explanation yielded by model; near 1 means virtually no error in model relative to data variability).

Note that nonlinear functions of the inputs, $X = (x_1, x_2, \ldots, x_n)$, are allowed but the weights remain first-order multiples of the inputs. Once the form has been assumed, a data set (*fitting set*) consisting of P, input-output pairs (X^j, y^j), where $X^j = (x_1^j, x_2^j, \ldots, x_n^j)$ and $j = 1, \ldots, P$ is used to fit the model, that is, to find the unknown parameters $(a_1, a_2, \ldots, a_n, b)$. To find these parameters, the input data and output data have matrix operations performed on them so as to find the unknown parameter values that minimize the sum of squared errors between the model's predicted value of y and the actual observed value of y for each pair. (Refer to Table 11.6.1 for the formula for sum squared error). Finally, an evaluation set (separate from but similar to the fitting data) may be used to evaluate the generalization ability of the model. (This brief review of linear regression should be supplemented by further reading if the reader is unfamiliar; see Ref. [1]).

Backpropagation and related neural network architectures use a training set (akin to the fitting set) to find unknown parameters of a model relating X to y. There, however, the straightforward similarity between the two methods ends. Backpropagation does *not* require the user to assume a priori a specific form of the function relating inputs to output(s). Backpropagation allows for nonlinear interactions between inputs and outputs in the model. While linear higher-order regressions also capture nonlinear relationships, they are confined to nonlinearities only in inputs (not parameters) and they must either be assumed a priori or found through tedious enumeration of possibilities. Backpropagation finds the weights of the network, like parameters of the regression, through iterative exposure to the training set, and often makes incremental changes to the weights in response to only a portion of the training set. This allows backpropagation to search for the best set of weights stochastically (while linear regression always finds the same set of parameters given a fitting set and a model). Backpropagation can find different solutions based on different starting points, ordering of patterns, choices for parameters, and so forth. The stochastic nature of backpropagation may allow it to find superior solutions. However, it makes backpropagation slower than regression and perhaps less stable. Finally, backpropagation differs from regression in its lack of discernability. A regression function, once specified, clearly describes how input terms contribute to an output value and straightforward statistical tests can answer numerous questions about its parameter values. A neural network function relating inputs to outputs defies easy explanation. However, researchers continually work to find ways to conduct tests on the results of neural network training applications so that a deeper understanding can occur. Overall, if an analyst possesses knowledge of the form of the regression equation, then standard statistical methods suit the application better than neural networks.

Goals of the Case Study

The case study will attempt to highlight and clarify some key misconceptions that often arise in neural network applications. We will discuss the reasons why the application of interest offers a viable alternative. While the approach to using neural networks can involve a certain amount of experimentation, helpful guidelines and manageable methods for structuring the approach do exist. These guidelines differ depending on the data at hand, so the case will present both the pilot study conducted and the full experiment. These two phases illustrate the variety of issues that can arise. A typical problem that occurs is overtraining, akin to the statistical problem of overfitting. The case will demonstrate awareness of the problem and approaches for avoiding or correcting it. Finally, another key issue that arises involves data. The data used for a neural network application contains everything the neural network will know about the problem; thus, it must adequately represent the relationship(s) of interest. Data division—into training and test sets—also presents an important challenge.

The case study is organized as follows. We begin with a description of the background of the problem and analyze the present situation. The objectives and scope of the project follow. The organization of the project is divided into two phases: the pilot study and the full experiment. The pilot study is briefly described, followed by a detailed plan for conducting the full

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experiment. The discussion then turns to the optimization approaches used. The ensuing modifications and results for the neural network approach follow. Finally, an assessment of the project together with a summary of practical findings completes the presentation.

BACKGROUND AND SITUATION ANALYSIS

Our case study examines a manufacturing plant with a quality problem. The fabrication of parts requires setting various parameters to affect part thickness. Thus, there exists a mapping from input (parameter settings) to output (part thickness). If the mapping were known mathematically, then an optimization method can attempt to set parameters so as to minimize deviation from desired thickness.

No accurate theoretical model for relating the control parameters to product thickness exists. However, the plant engineers recognize which factors affect thickness: temperature of the material, speed of roller, feed rate, grade of material, machine, and operator. The last two factors are considered because the parts are fabricated on one of four different machines, which perform differently due to age; one of four operators, each of whom has a unique approach, operates the machine. Target (desired) thickness varies, depending on the customer for whom the part is being produced.

Currently operators use a handbook to set the temperature, speed, and feed rate parameters to certain values based on the grade of material and desired (target) thickness. Thus the handbook provides a model of sorts that leads to a thickness, y^e, when thickness y is desired. The handbook model results in a current approximate average deviation from desired thickness of 3 mm as measured by root mean squared error (RMS). (See Table 11.6.1 for definition of error terms used in the case and Ref. [1] for a detailed background discussion of statistical issues.) The handbook recommendations are presented in a table, which is of necessity restricted in its usefulness. For example, the temperature parameter is not truly controllable, and indeed the ability to set it to some values depends on the grade of material. Furthermore, the current approach treats all parameters as discrete, which can take on one of four values. In reality, only two of the six parameters are discrete (operator and machine). All other factors take on continuous values. In addition, the handbook settings do not account for differences between machines or operators at all. Thus, the current method for setting parameters has a number of flaws. It does not accurately capture the relationships between the inputs and the output: thickness.

The group assigned to the task of improving product quality aims first to understand the relationship of controllable factors to thickness. The approach taken must be easily implemented, low in cost, and effective (resulting in improvement over the current approach). Since a great deal of data is readily available at the plant, the group decides that an empirical method will suit the project and prove reasonable in cost. Given time and production costs, they determine that they may take up to 4000 observations (at 500 parts produced per day, eight days of data collection needed) on the contributing factors and related thickness. The group intends to determine the relationship from this data and use it to improve product quality.

A preliminary analysis on an existing data set of 200 observations used linear regression and revealed that a first-order model provided an R^2 of only 0.5 (see Table 11.6.1). This performance corresponds to a deviation (RMS error) of 2.8 mm. Further analysis showed that the parameters exhibit at least second-order interactions. Therefore, an effective linear regression approach must include higher order effects, which can become much more complicated. The linear regression model only slightly improves the current results, so the group considers using a neural network approach.

The existing conditions make this manufacturing plant an excellent candidate for a neural network. First, data can apparently be obtained in large quantities without excessive cost. Certainly, this is not always the case in a manufacturing setting. Sometimes, much smaller amounts of data are used in a neural network application, as we will see in the subsequent section, Examples of Neural Network Application. Some research suggests that backpropagation may be better able to construct empirical models with less data than statistical approaches, but empirical modeling always benefits from access to as much data as possible. Second, the standard linear regression approach (which can be done using spreadsheet or other software rather easily) shows tremendous room for improvement. Third, there do not appear to be satisfactory theoretical relationships that can accurately predict the output thickness based on any values of the inputs; while the handbook gives some specific values of the relationship it does not offer an equation that can be used for all possible situations. Finally, the task at hand suits an empirical approach to the building of a model relating a set of inputs to an output value, and the neural network approach does not require specification a priori of the functional form as would a regression.

OBJECTIVES AND SCOPE

Understanding exactly how the various controllable factors affect part thickness is critical to any effort to improve quality. The company defines quality as the lack of deviation from target thickness. Thus, the objectives of the project are twofold. First, they aim to accurately describe the input-output relationship for quality, where input is the vector (temperature of the material, speed of roller, feed rate, machine, operator, and grade of material) and output is the thickness of part, in mm. Second, they wish to use the analytical relationship in an effort to produce parts in the target range for thickness. The emphasis of this case discussion is on the first objective—building the empirical model with a neural network.

Once a dependable model exists, the group will use optimization and/or search methods to find ways to prescribe parameter settings to achieve desired thickness. Essentially, the handbook currently used now performs this task. Operators look up prescribed settings for feed rate, speed of roller, and temperature based on material grade and desired thickness. Sometimes they must settle for approximate answers because the handbook cannot account for operator and machine differences. Moreover, it treats all parameters as discrete.

Given the objectives and scope of the project, the group decides on the application of neural networks to the problem. Further, the group has access to inexpensive software for implementing the widely used backpropagation network. They choose to use this network due to its popularity and documented use. Even though other network models exist that may suit the problem at least as well with certain advantages over backpropagation, the group recognizes the ease with which backpropagation may be implemented and the resources available to aid those who use it as critical factors in their decision.

ORGANIZATION OF PROJECT

The group organizes the project into two phases. First, they will run a pilot study using the available data. This attempt will elucidate some of the issues surrounding the application of neural networks to their problem, help to familiarize them with the software, and provide a comparison with the linear regression results. In the second phase, the team will collect data and analyze it thoroughly using neural networks.

Phase One: Pilot Study

The existing data set contains 200 observations (each observation corresponds to a part). All 200 observations were used in the linear regression approach. The group decides to use half for training and half for testing of the neural network. Deciding how to divide the data can prove critical, so the team looks into various options. They learn that when data is provided, not generated, and relatively scarce, these options for data division include using the duplex algorithm from statistics theory [1], randomly splitting data, or looking for other obvious ways to divide data that try to ensure similarity between the two sets. The group opts for randomly splitting the data and checking it by means of variance of the output variable (thickness) to eventually find a split that ensures a sufficient degree of similarity.

After splitting the data, they choose a 10-hidden-unit architecture (the typical abbreviation is the number of input, hidden, and output units, or, in this case, a 6-10-1 network) and train it using the backpropagation algorithm until the RMS error reaches an acceptable value. The default value for the software is 0.2. After an hour of training, the network shows no sign of reaching even an RMS error value of 2, so the team stops training after an additional hour (when RMS error = 1.3). This corresponds to an R^2 of 0.9. The result for the test set, however, is an R^2 of only 0.3. The network, it turns out, has probably experienced overtraining. It has a large number of parameters (there are 70 connection weights and 11 bias weights—one for each hidden and output unit—which are explained in Refs. [2,3]) relative to the amount of training data (100 observations), and it continued training until the error approached an arbitrary RMS error value, which as the R^2 illustrates, is actually quite low for this data set. The group reinitializes the network with half as many hidden units, trains for half as long, and obtains significantly improved results (R^2 of 0.87 training, 0.8 for test). Recall that the linear regression resulted in an R^2 of 0.5. The group recognizes a certain amount of arbitrariness in their approach and attempts to learn more about training the neural network, as will be discussed in the next section. With the lessons learned, they plan the full experiment.

Phase Two: Full Experiment

This phase represents the full experiment, so the team outlines the approach based on what they have learned in phase one.

Collect Data. The group decides that they should generate the data used in order to more carefully control the experiment. Fortunately, their budget allows them to take up to 4000 observations. As we will see when we examine neural network application examples, this number will allow them to use a full factorial experimental design to generate data for three separate sets.

Divide Train/Monitor/Test Sets. In the pilot study, only two different sets (train and test) are used. Further investigation teaches the group that with more data a better approach would employ three different sets: training, monitoring, and testing. Data used to find the weights of the neural network is the training set, that used to assess the network's predictive capabilities is the test data, and that which is used to monitor the progress of training is the monitoring set. The three-set approach will play a key role in reducing some of the arbitrariness associated with the neural network approach and will be described in more detail later in this chapter. Since the sets will generate their own data, splitting them into separate sets will pose less difficulty than it did in the pilot study.

Scale. Although often overlooked, the process of scaling data can significantly improve modeling results. Fortunately, most software packages automatically scale data. For backpropagation neural networks, a typical approach is to scale each input and output value linearly between its minimum and maximum values. Thus, the scaled value of an input, x, become x_s where $x_s = (x - x_{\min})/(x_{\max} - x_{\min})$ to scale x between 0 and 1, or $x_s = [2(x - x_{\min})/(x_{\max} - x_{\min}) - 1]$ to scale x between (-1) and 1. The process of scaling data, however it is done, turns out to be surprisingly important. Since the group chooses to use the default settings for the backpropagation network, they will scale data to the (0,1) interval (and use a sigmoid transfer function for hidden units).

Neural Network Design. Much has been written about the process of selecting the optimal architecture (number of hidden units, and hence weights) of a neural network. The group intends to use some practical rules of thumb to streamline this decision process. By considering the interrelationships between number of parameters (weights) in the neural network, length of training time, and data, it is possible to reduce the difficulty of this decision. Again, the three-set approach plays a crucial role in simplifying the choice.

Train. The software available has a utility that allows the user to select the type of training desired. Default training requires the user to set a tolerance value for error, and when the neural network's predictions reach this level, training ends. The group attempted to use this approach for the pilot study. The three-set option periodically checks the monitoring set of data (similar to but different from the training data) and ends training when the error on that set ceases to decrease. As with most neural network software, data will be presented in random order during training. In most cases this randomized presentation order proves essential to success in training.

Assess. A third set of data (test set), again similar to but different from the training and monitoring sets, allows the user to assess objectively the performance of the network. After reading some background statistics and neural network material, the group agrees to use the R^2 measure on the test set to objectively assess performance.

The R^2 measure for training data has less value unless it is adjusted by the number of parameters in the model. Unfortunately, the number of effective parameters for a neural network is not straightforward to determine [6]. Some insight may still result from using the unadjusted R^2 for the training set, however. If it is quite low (indicating the model cannot explain variability in the data), it may well indicate that the architecture (number of hidden units, primarily) is not sufficiently large or complex to adequately model the relationship.

Optimization. Once a satisfactory mapping has been obtained, optimization tools may be used to find prescribed values for parameters that lead to parts with minimum deviation from target thickness. Obviously, the mapping obtained will contain some error due to its empirical nature, but the optimization can still help to find combinations of parameters likely to be effective in controlling quality. Moreover, the optimization stage can also be used to find prescribed values for a subset of parameters, given values for the remainder, which more typically reflects the needs of the operators. Finally, a given combination of parameter values may be improved upon using the optimization approach.

PROCEDURE AND APPLICATION OF TOOLS

Neural network applications vary in many ways, but all require a sufficient amount of representative data, an understanding of the problem deep enough to determine the important contributing factors (inputs), and experience enough with neural networks to appropriately apply them. Some alternative examples of neural network applications, along with the relevant issues surrounding the instance and any interesting outcomes of the example, are presented in the following section. After gaining a broader appreciation for the variety of ways neural networks can succeed (or fail), we will then explore the specifics of our case study.

Examples of Neural Network Application

As a search of the literature will quickly demonstrate, the number of documented neural network applications has soared in the past decade. Unfortunately, not all documented cases prove that the neural network approach accomplished anything unusual. Some, of course, demonstrate failure outright, but even those that claim success may not actually confirm much. At least a comparison to simple, first-order linear regression ought to be reported as well as a comparison to existing approaches (if any exist, other than regression). Detailed descriptions of how data is obtained, split into training and testing sets, and how the neural network architecture is selected and trained should also be included.

Neural networks have found widespread application in the financial sector, where data is readily available. In one application, they were used to predict the long-run operating performance of new ventures so that the pricing of an initial public offering (IPO) could be assessed [7]. The authors made a comprehensive comparison to an appropriate technique from regression. They obtained data from a publicly available database. The entire set of data, 462 input-output pairs, was divided randomly to yield training and test sets of 231 examples each. The number of hidden units was selected according to a relatively arbitrary rule of thumb, and training was stopped when training error leveled off. The authors found that backpropagation did, overall, yield some improvement over linear regression.

Using neural networks for prediction and forecasting appeals to many analysts. Hill et al. [8] describe a recent comprehensive study of neural networks for forecasting that compares backpropagation to many conventional models. Examples of how some neural network decisions were made follow. First, they studied performance on monthly, quarterly, and annual data. For annual data, they chose three input nodes representing years $(t-2)$ to t, and one output node representing year $(t+1)$. For monthly data, they used nine input nodes representing months $(t-8)$ to t, and one output node for month $(t+1)$. They used two hidden nodes for annual data networks and four for monthly data networks (found by trial and error: first, they used two, then four nodes, and then selected the best performers). They used 111 series to train the networks and stopped training according to several criteria, one of which was observing progress in reducing the total error term (much like the previous example). The neural networks performed comparably to conventional forecasting techniques for annual data, but significantly better for quarterly and monthly data. Therefore, they deduced that neural networks possessed an ability to handle discontinuities in data—typical in product and inventory forecasting problems.

Wang [9] describes a comparison of backpropagation with regression techniques. The goal is to predict the fraction of available chlorine in a product in which this fraction decreases over time. Although there are only 44 observations in the data set (half of which are used for training and half for testing), and only one input variable, the network selected has eight hidden nodes. After 166,000 learning cycles (corresponding to a few minutes on Pentium-90 MHz PC), the network generates a satisfactory regression function performing considerably better than linear regression. This example illustrates that an appropriate number of hidden nodes reflects the difficulty (level of nonlinearity) of the problem, not the dimensionality of the input or the size of the training set.

Data Generation

The actual procedure undertaken for the case begins with data generation. Time and cost constraints limit the project to a total collection of not more than 4000 observations of the six input–one output relationship. To divide the data into three sets, each would contain approximately 1300 observations. As discussed earlier, the group hopes to use a full factorial design of experiments to generate data. They decide on an experiment using three levels for four of the parameters and four levels for the other two parameters (operator and machine). This leads to a total of $(3^4)(4^2)$ or 1296 observations. Since the training set should consist of approximately 1300 observations, this result is quite convenient. For the monitoring and test sets, the same experiment can be used so that the sets are highly likely to contain comparable, but different, data. However, they decide to perturb the values of the continuous variables slightly so that the input combinations will not be identical for all three sets.

Design and Training of Network

The architecture of the neural network dictates six input nodes and one output node, but *best* number of hidden units is not so obvious. The decision to use periodic monitoring can reduce the difficulty of this choice.

The three-set approach recommends choosing a *sufficiently large* architecture (number of hidden units). Then, periodically check the error on the monitoring set throughout training. Stop training when the error on the monitoring set reaches a minimum (no longer improves) to prevent overtraining. The group begins by considering the maximum possible number of hidden units: 50 for their software package, since they wish to have a sufficiently large network. They reason that in statistics an oft-quoted rule of thumb says that a model with one fifth as many parameters as observations will probably suffice. The 6-50-1 neural network contains 401 connection weights for 1300 observations, so it is reasonable to believe that the model is probably sufficiently sized ($401 >> 1300/5$). The danger, however, is that such a large network could overfit the data. That is, the many parameters (weights) of the model could begin to fit noise in the data and actually learn the input-output relationship of the training set so well that it is unable to generalize to new data (such as that in the test set). Furthermore, the large number of hidden units may require excessive training time.

The three-set option should help to avoid overfitting by considering that the weights of a neural network do not all contribute to error reduction. Initially, the neural network model uses only a very few of these weights as effective parameters [6]. As training progresses, more weights become effective in the modeling process. If the neural network has a large number of weights with respect to the number of observations (and difficulty of mapping), and if training is allowed to progress so long that many or all of these weights become effective parameters, then overfitting may occur. However, the approach can avoid the problem by stopping training before overfitting occurs via assessment of the error on the monitoring set.

Even so, the three-set approach can only monitor error at discrete increments (counted as presentations of data points) during training. The finer the increment, the better the chance that overfitting will not occur—but the process will consume a great deal of time. The default increment for their software package is 100; thus, after every 100 presentations of training data, training is stopped and error on the monitoring set is checked.

Given the information obtained and the limitations imposed by their software, the group decides to use a smaller 6-40-1 network with 321 connections. They still feel the network size should be sufficient ($321 > 1300/5$) but not overly so and will not push the boundaries of their software. Conventional wisdom prefers fewer parameters and finds smaller models more efficient. After their experience with the pilot study (having seen the effects of overtraining firsthand), the group opts for the smaller, still sufficiently large network.

Assessment Issues

A common mistake occurs when a neural network user trains the weights of the network until it reaches a prespecified error level, and uses that error level to assess the network. Since the objective of backpropagation is to minimize the sum squared error (SSE) between the actual and desired output values, SSE is often used to assess a network (or some function of SSE, such as root mean squared error).

While the SSE can help in comparing network results for identical sets of data, it does not take into account the variance in the data set that can drastically alter what we mean by *good performance.* For example, consider what happened to the group during the pilot study. One of the methods used for splitting data led to a very low variance of the output value (total sum of squares [TSS] = 40) in one training set and a much higher variance for another training set (TSS = 10000). (Both sets contained 100 data points.) Now consider the SSE values for two neural network approaches. The SSE resulting from using the first set of data seems quite low—10. For the second set of data, the SSE is much higher—1000. While the SSE for the second set is 100 times higher than for the first, the performance of the second is actually much better. We can factor in the variance by using the R^2 measure, 1-SSE/TSS. Thus for the first approach, $R^2 = 1 - 10/40 = 0.75$. In the second case, the R^2 is 9000/10000 or 0.90, which is much higher. Although a technical interpretation of these numbers requires a bit more insight, this example helps clarify why error alone can be misleading in assessing performance of any empirical method.

Optimization

Once they find a satisfactory function relating inputs to outputs, the group hopes to use it in an optimization strategy. There exist two approaches to the task. The first is to use the input-output model provided by the network to systematically provide recommendations or check existing configurations. While not truly an optimization strategy, this approach makes use of the model by repetitive application. Since the trained network is simply a collection of nonlinear functions, it provides an output on the basis of a set of inputs nearly instantaneously. Thus it is even possible to conduct a brute force search to optimize the output. One important aspect of optimization discovered by the group is the necessity to remember to scale data for the computation of predicted outputs.

In the brute force search, a subset of input parameters $(x_1,\ldots,x_s)$ are fixed. For example, these might correspond to x_1 = temperature, x_2 = grade of material, and x_3 = operator. The remainder $(x_4,\ldots,x_6)$ are free to be optimized. Then the brute force approach simply searches over values of the free variables and records the best associated output value (where outputs are obtained by using the neural network model). For example, if all but one parameter is fixed, then the approach is particularly effective. Say the parameter can take on values between 0 and 100. Assume that is reasonable to search in increments of 0.1, for this parameter. Then 1000 values are examined, each time computing the predicted output from the neural network model. Obviously, for any computer this search would take negligible time. If, on the other hand, two parameters were free and the approach for each was the same as just described, then 1,000,000 computations are needed. This may still be relatively efficient, depending on the computer available. But if finer increments are needed for several parameters, this approach may consume too much computer time. In such cases, we turn to more sophisticated search techniques.

The Nelder-Mead simplex approach is a more sophisticated technique from the field of nonlinear optimization for finding the optimum solution to a problem [6]. In our case, the problem may be mathematically stated: Minimize deviation from desired thickness, where deviation = $(y - y^e)^2$ and $y^e = f(\mathbf{x})$. [Again y = desired thickness, and y^e = estimated thickness provided by neural network, and $\mathbf{x} = (x_1,\ldots,x_6)$: the set of input parameters].

The function $f(\mathbf{x})$, generally highly nonlinear, is provided by the neural network. Any of the variables x_j may be fixed or free, depending on their controllability. The Nelder-Mead downhill simplex algorithm is a well-known, widely implemented approach to derivative-free nonlinear optimization. The algorithm, in general, cannot guarantee that it will find a global optimal solution to a given problem, but rather a local optimal solution. The quality of the solution provided depends on the starting point of the search. It can be run several times from different starting points, and the best solution obtained taken as the recommended solution. Computer code can be obtained via a number of libraries or by referring to Ref. [10]. The code computes the local minimum of a function $f(\mathbf{x})$. After obtaining and modifying the Nelder-Mead code as needed, the group uses the code as follows:

1. Over all possible values of the vector $\mathbf{x}$, find $\mathbf{x}^*$ such that $f(\mathbf{x}^*)$ is minimum.
2. For given values of $(x_1,\ldots,x_s)$, find the remaining $(x_{s+1},\ldots,x_6)$ to minimize $f(\mathbf{x})$. Thus, for example, if the values of parameters temperature, machine, and operator are fixed, the algorithm will find the optimal values of the remaining parameters that are free to be adjusted.

3. Given a vector of parameter values **x,** use Nelder-Mead to find the *nearest* local minimum vector **x***. Recall that the output of the Nelder-Mead algorithm depends on its starting point. If the starting point is selected as a given combination of parameter values, running the algorithm will return the nearest local minimum. This may be useful when the nearest optimized recommendation to a current setup is needed.

IMPLEMENTATION OF CHANGES AND IMPROVEMENTS

The first neural network results obtained distress the group. Watching the plot of SSE during training, they find that it falls minimally at first, then levels off without improvement for some time. (This illustrates an excellent use for the SSE measure.) Although they restart the training process, they find this happening repeatedly. After some exploration, the group discovers that although the (0,1) sigmoid activation function is historically important, it has significant drawbacks. The behavior they have observed, it turns out, is quite typical. The choice of the (0,1) interval leads quite often to node activation values of zero, which can cause the network to "freeze" and essentially stop training. A simple alteration—using the interval (−1,1)—corrects the problem. Most neural network software enables users to select such an interval by implementing a hyperbolic tangent activation function or another logistic function that is symmetric about zero.

Even then, the results obtained for the network disappointed the group. The final test set error (SSE) corresponded to an R^2 of only 0.6 (and training set R^2 of 0.7)—a minimal improvement over linear regression. To decide how to proceed, the group needs to look at both training and monitoring set performance. If both training and monitoring set performance are unsatisfactory, then it is likely that the neural network actually needs more weights (by adding hidden units, we increase the number of weights). However, there may be other problems causing the unsatisfactory results. The essential problem is that the neural network does not contain a sufficient number of useful parameters to model the mapping.

On the other hand, if the training R^2 were quite high compared to the test set error R^2, then overtraining may have occurred. This can happen despite the use of a monitoring set when the underlying function is not highly nonlinear, the number of weights is extremely large in comparison with the number of observations, and the monitoring set error is checked at increments that are too far apart. Unfortunately, smaller increments lead to a longer period of training so most approaches attempt to strike a balance.

In this case study, since training and test set error levels were similar and unsatisfactory, the group decided to increase the number of weights. Recall, however, that they can add only 10 more hidden units at most (due to software limitations), corresponding to an additional 80 connections. Adding 10 more hidden units leads to 50 total hidden units, which represents the maximum number allowable using their software. However, there do exist other options for increasing the number of weights for a neural network. First, it is possible to add connections that skip layers—connections directly from input to output units (a total of 6 additional connections result from this strategy). These connections would directly model linear relationships between inputs and outputs. Even when the function is highly nonlinear, such connections prove useful because they prevent the network from using nonlinear functions to model the linear aspects of a mapping. The network can then focus its nonlinear abilities on the correspondingly nonlinear aspects of the mapping.

Alternatively, or in addition, a second layer of hidden units may be added. Since connection weights, not hidden units, provide the potential parameters of the network, adding a second layer can prove quite effective. For example, the number of connection weights for a 6-40-5-1 network is 491 versus only 361 for a 6-45-1 network. Thus, for the same number of hidden units, the group can obtain more powerful computation (more parameters) with the 6-40-5-1 network. They decide to try this option.

RESULTS AND FUTURE ACTIONS

The new results indicate success for the project. The test set R^2 rises to 0.80, which the group deems a significant improvement. In conjunction with their strategy for optimization, the group discovers that their approach reduces average deviation from target thickness to 1.1 mm, whereas the current average deviation is approximately 3 mm. The improvement is due to both the more accurate model provided by the neural network, and to the more flexible approach offered by optimization (either brute force or Nelder-Mead). Recall that, currently, operators check the handbook for recommendations on settings that are artificially discretized, ignore machine and operator differences, and assume temperature of the part to be controllable.

Using an optimization approach together with the neural network model makes use of the ease with which the model associates inputs with outputs. However, it should be noted that regression will result as easily as in a computable model. Furthermore, the neural network model does have some disadvantages. Like any empirical approach, it must contain error. The optimization approach cannot guarantee finding anything but a local optimal solution.

Overall, the group found the neural network approach reasonably easy to use and highly effective. The summary of their practical findings for this application follow. First, use a logistic function for the hidden layer units that is symmetric about zero [providing output in the range (–1,1)]. If sufficient data exists, try the three-set approach with periodic monitoring. If not, carefully assess results for overtraining, and reduce the number of hidden units if training set performance far exceeds that of the test set. Alternatively, stop training when training set error reduction begins to slow considerably. If neither training nor test performance is acceptable, consider adding hidden units, connections that skip layers, or an entire additional layer of hidden units. Use the R^2 measure to obtain a clearer picture of model performance, although SSE can be useful in assessing performance during training.

Neural networks can prove quite useful as an alternative approach to certain problems. They have found application in the financial sector, for manufacturing problems wherein data can be readily obtained, and for forecasting and other prediction problems. Key conditions that support the use of neural networks include the following:

- Data is available or easy to obtain—the more data, the better.
- Empirical modeling approaches fail; linear models do not perform acceptably and no known functional form for higher order or nonlinear regression is available or effective.
- Expert systems do not prove practical because no expert can articulate the rules that can associate inputs with outputs.
- A good understanding exists of what inputs affect the output of interest.

When clear-cut rules exist that relate inputs to outputs, then an expert system may prove a better choice; if knowledge about the problem leads to a reasonable expectation of what kind of functional form a regression might assume, then conventional statistics may provide a better approach than neural networks. Exploiting the great potential that neural networks possess depends on their being applied when appropriate, not when existing approaches can succeed well, and in being applied correctly.

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BIOGRAPHY

Laura Burke was an associate professor of industrial engineering at Lehigh University who currently stays at home with her children. Over the past decade her teaching and research interests have focused on a variety of neural network applications to manufacturing, logistic, and other engineering problems. She holds a B.S. and M.S. in industrial engineering from Pennsylvania State University and a M.S. and Ph.D. from the University of California, Berkeley.

SECTION 12

INFORMATION AND COMMUNICATION MANAGEMENT

CHAPTER 12.1

BAR CODES AND OTHER AUTOMATED DATA COLLECTION METHODS

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This chapter will describe the automated data collection technologies that have received widespread usage in recent years. A thorough review is given for bar codes, two-dimensional bar codes, and wireless data collection technologies. Descriptions of pen-based computing, chip cards, contact memory buttons, automatic speech recognition, and magnetic stripe cards are also given. The work includes a technical description of the technology, typical applications, selection criteria, and in some cases, implementation considerations. Future trends are also discussed, including a discussion of direct mark bar codes for permanent marking, potential applications of radio frequency identification, and total wireless computing and data collection environments.

BACKGROUND

The search for faster, more effective systems to aid in data collection and transmission is a continuous one, with the directions being set by advances in technology. *Automated data collection* (ADC) is a term to describe families of technologies that aim to immediately identify physical objects with 100 percent accuracy. In addition, ADC technologies allow data to be passed in real time to any database, software, or computer system, providing the capability for a user to make informed decisions in very short times. For a company, these features provide such benefits as reduced labor hours, reduced processing and shipping errors, and accurate inventory records [1].

AIM^{USA}, the industry trade organization for ADC manufacturers, categorizes ADC technologies into five distinct families: (1) optical, (2) wireless, (3) cards, (4) biometric, and (5) contact memory. Table 12.1.1 lists the technologies comprising each of these categories. This chapter will describe select technologies from each ADC family listed in Table 12.1.1. Unfortunately, space restrictions do not allow a thorough discussion of all of the technologies. Those technologies that are currently in widespread usage or that show promise as a future trend will be discussed. Discussions will focus on the basic structure of each ADC technique, its benefits, its common applications, the tools associated with the technology, and selection criteria.

TABLE 12.1.1 The Technologies of Automated Data Collection

ADC family	ADC technology
Optical	Bar codes Two-dimensional bar codes Optical character recognition (OCR) Machine vision systems
Wireless	Radio frequency data communication (RFDC) Radio frequency identification (RFID)
Cards	Magnetic stripe cards Magnetic ink character recognition (MICR) Chip cards Optical (laser) cards
Contact	Pen-based computing Touch screens Contact buttons
Biometric	Automatic speech recognition Hand geometry Retinal eye scan

BAR CODE DATA COLLECTION

The most widespread ADC technology is *bar coding.* Bar codes are used in many industries, including manufacturing, food, retail, health care, transportation, and distribution. Bar code applications are material- or people-tracking systems. They typically include such applications as work-in-process tracking, baggage tracking, small-package tracking, book tracking, statistical process control, time and attendance, patient tracking, blood tracking, and access control. In addition, for quick retrieval of patient or client files these systems have recently begun to find their way into such areas as insurance companies, law offices, and dental offices.

The major benefits of bar codes are the speed and accuracy of the data collection task. Information encoded on a bar code symbol is typically a key that allows database lookups to occur. By scanning a bar code symbol, not only is information collected faster than with manual data entry, this information is typically passed on a real-time basis to a host computer for immediate processing. Accuracy of data is also better with bar code scanning systems. Using manual keypad data entry, an error occurs once in every 300 characters entered. However, with bar code scanning, an error occurs only once in every three to four million characters entered. If a check digit is available on the bar code, then error rates are virtually eliminated.

Bar Code Symbol Structure

A bar code *symbol* consists of a parallel arrangement of bars and spaces of varying widths. The particular arrangement of bars and spaces represents characters encoded into the sym-

BAR CODES AND OTHER AUTOMATED DATA COLLECTION METHODS

bol. A *symbology* is the set of rules for specifying the way characters are encoded into bar and space widths. Each symbology has a character chart that assigns particular bar/space patterns to individual characters. Well-known symbologies include Code 39 and UPC.

Each symbol consists of five required parts: (1) quiet zone, (2) start character, (3) data characters, (4) stop character, and (5) quiet zone. This structure is illustrated in Fig. 12.1.1. Alternatively, some symbologies allow a check character immediately before the stop character [2].

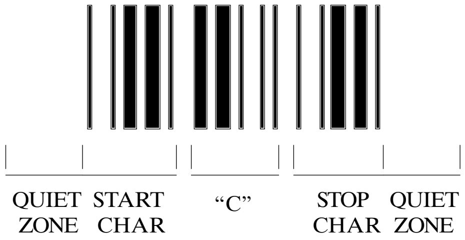

FIGURE 12.1.1 A Code 39 symbol encoding the character “C.”

The quiet zones on both ends of the symbol are clear spaces containing no dark marks. The quiet zone precedes the start character of a bar code symbol and follows the stop character. They serve to indicate to the scanner where the next bar code symbol begins.

Start and stop characters serve several purposes. First, they uniquely identify a symbology, as every symbology will have a unique start/stop character combination. This feature will allow a scanner to autodiscriminate among various symbologies. Second, they allow the scanner to determine the direction in which the scan was made. Most bar codes can be read left to right or right to left. The start/stop characters indicate this scanning direction. Finally, they indicate to the scanner to begin reading data past the start character and to end reading data when the stop character is encountered.

Between the start and stop characters lie the data characters comprising the data content of the symbol. Each data character is based on a series of bars and spaces of preassigned widths. Each symbology will have a unique character set to describe the bar/space patterns corresponding to characters allowed in a symbol. Figure 12.1.2 illustrates a portion of a Code 39 character set. Check characters ensure data accuracy when a bar code symbol is read. Check character schemes are mathematical computations involving the characters encoded into the symbol and are appended to the end of the symbol. When the symbol is decoded, the scanner performs the same computations, and, if the result is equivalent to the check character value encoded on the symbol, then the scan is considered to be valid.

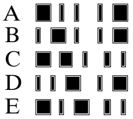

FIGURE 12.1.2 Sample from Code 39 character set.

Commonly Used Symbologies

Over the years, hundreds of bar code symbologies have been developed and accepted as standards. The reason for such a variety of symbologies is due to the vast number of different applications to which this technology may apply. Different symbology standards exist for the retail, manufacturing, health care, automotive, small-package delivery, electronics, and other industries. In this section, we will describe several of the most widely used symbologies and their common applications.

UPC. The *Universal Product Code* (UPC) has been adopted as an international standard for the retail industry. This symbology is found on all grocery products, clothing tags, magazines, and most over-the-counter drugs. Unlike other symbologies, UPC is both a coding scheme and a symbology. As a coding scheme, UPC identifies a product and its manufacturer. There are three versions: Version A (a 12-digit symbol), Version E (six digits), and Version D (variable length). The most common UPC symbology in the United States is Version A. It is a 12-digit code separated by start and stop patterns on either end and by a middle pair of *guard* bars (Fig. 12.1.3). Five digits on the left side of the guard bars represent the manufacturer of the item. The five digits to the right of the guard bars represent a unique product identifier code. The 12-digit code also includes a number system digit indicating the type of product the symbol is representing (e.g., drug, coupon, consumer package), and a check digit.

0 12345 67890 5

FIGURE 12.1.3 UPC Version A symbol.

Code 39. Code 39 is the world's most widespread industrial symbology. This symbology is supported by more scanners, printers, software, and industry standards than any other symbology. Code 39 is an alphanumeric symbology (Fig. 12.1.4). It can be expanded to encode the entire ASCII 128 character set. Code 39 can be any length, so that large or small amounts of data can be encoded into it.

Code 39 is sometimes termed Code "3 of 9." A Code 39 character is comprised of five bars and four spaces, summing to a total of nine elements. Of the nine elements, three are wide and six are narrow; hence the name Code 3 of 9. A Code 39 symbol begins and ends with an asterisk encoded as its start and stop characters.

Code 39 is self-checking, that is, a single printing defect cannot cause a substitution error. Therefore, the symbology does not normally include a check digit. However, an optional check digit can be applied with most bar code printing software for those applications that require high security or where print quality of the symbol is poor.

A B C D 1 2 3 4 5

FIGURE 12.1.4 Code 39 symbol.

Code 39 has been adopted by many industry standards groups. It is the only accepted standard for military products adopted by the LOGMARS Council. AIAG, the Automotive Industry Action Group, has accepted it as the standard for automobile component manufacturing, and HIBCC, the Health Industry Bar Code Council, has accepted it for critical applications such as blood banking. Printed standards are readily available from each of these groups.

Code 128. Code 128 is a high-density alphanumeric symbology (Fig. 12.1.5). It is a variable length, continuous symbology with multiple element widths. When used for numeric data only, Code 128 can have a density of over 24 characters per inch. Code 128 has been adopted by three industry standards groups. The Uniform Code Council (UCC) and the International Article Numbering Association (EAN) have both recommended Code 128 for shipping containers for the apparel industry and distribution. The Voluntary Industrial Communication Standard (VICS) has suggested Code 128 for all containers in distribution.

a b c d 1 2 3 E F G H

FIGURE 12.1.5 Code 128 symbol.

Symbology Selection Criteria

When choosing a bar code symbology, several basic questions should be asked. First, is the application that requires a bar code an internal application or external application? If it is an external application, where symbols are placed on a product or package for a customer to scan, then the choice of the symbology may already be dictated by industry standards. If the external application is for the retail industry, then UPC will more than likely be the required symbology. If the product is to be used by the Department of Defense, then Code 39 will likely be selected.

If the application is an internal application (such as material tracking on a shop floor), then the following types of questions should be asked: What is the type of data to be collected—alpha, numeric, or alphanumeric? What is the available printing area on the product or object to be tracked? How much data needs to be encoded on a symbol? What types of printing and scanning equipment are already available that may be used? What symbologies does this existing ADC equipment currently support? Answers to these questions will likely narrow the choices for a particular symbology.

Readers

A *bar code reader* is a device that extracts information that is optically encoded in a bar code symbol and then converts it into computer-compatible digital data. A reader employs electro-optical techniques to scan the bar code symbol. Depending on the type of reader used, the scanning motion may be provided by an operator, the reader's internal mechanism, or the bar code symbol itself. A reader consist of two major devices: (1) an input device and (2) a decoder. The input device serves to illuminate the bar code symbol with light energy, then examines the amount of light reflected from a localized area of the symbol. A bar code symbol's spaces will reflect more light than the bars. The decoder serves first to convert the light energy to a digital format, then to translate the digital data to human readable characters. Depending on the type of reader, the input device and decoder could be separate units or housed within a single unit.

Bar code readers respond to the optical reflectivity differences between a symbol's bars and spaces at a particular wavelength of light employed. The most common wavelength band used by bar code readers is centered at 633 nanometers. The second-most-common wavelength band, most often used for infrared reading, is centered at 900 nanometers.

Readers may be of several types. They may come into contact with the symbol or be non-contact. They may be fixed-mount or handheld. In this section, we will describe several widely used reader technologies. These include scanning wands, laser diode readers, and CCD readers.

Scanning Wands. Scanning wands (Fig. 12.1.6) physically touch the symbol that is being scanned. The light beam emanating from the wand is fixed with respect to its physical housing; therefore, the scanning motion must be provided by the operator. Wands operate by flood-illuminating the symbol, then creating a spot by focusing the light through an aperture.

Until the invention of the laser diode scanner, wands were the most commonly used bar code readers. Their popularity was due to their simple structure, their low product cost, and

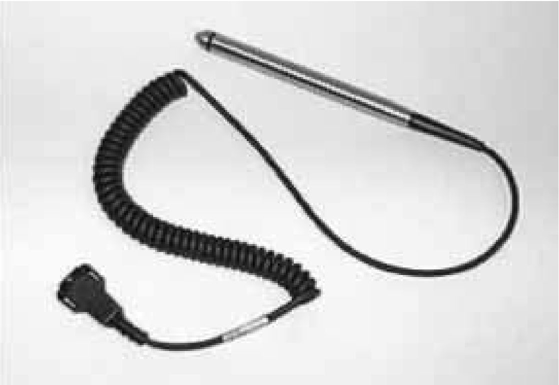

FIGURE 12.1.6 Scanning wand.

their ruggedness in harsh environments. Their decline in usage has been due to the skill that is required of an operator in performing the scanning motion. Typical mistakes include scanning too slowly, stopping the scan before reaching the trailing quiet zone, not starting the scan in the leading quiet zone, or scanning past the symbol's vertical bars. In addition, the time to scan a bar code symbol with a wand is much slower and less reliable than any of the noncontact reading technologies currently employed.

Laser Diode Readers. The most widespread bar code reading technology in usage today is the handheld laser diode reader (Fig. 12.1.7). These solid-state devices scan a bar code symbol at the rate of more than 40 scans per second. The advantage of this technology is that little operator skill is necessary to perform the scanning operation. In addition, symbols that have poor quality can still be successfully scanned due to the large number of scanning attempts per second.

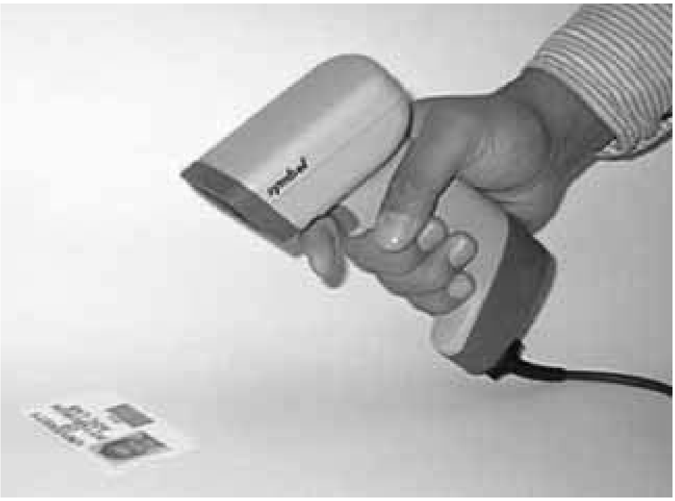

FIGURE 12.1.7 Raster laser reader.

Laser scanners typically provide the scanning motion through the usage of an internal electromechanical system. Often, this technology employs oscillating mirrors that serve to direct the laser beam in a back and forth motion across the symbol. An advantage of using a laser beam for scanning is that the operator has available a large range in the distance from the reader to the symbol at which a scan may be done. Depending on the symbol's X dimension, these scanners typically scan a symbol from as close as 2 inches out to approximately 14 inches. Some applications, such as scanning products in warehouses, use customized laser readers that successfully scan a symbol from a distance as far as 80 feet.

To meet the increasing need for reading two-dimensional bar codes, handheld raster laser scanners have been developed. These devices have both a deliberate horizontal and vertical scanning motion built into their internal mechanism. Scan rates are much higher than with the conventional laser scanner. Typical horizontal scan rates are about 400 scans per second, with vertical scans on the order of 10 scans per second to cover the entire rectangular area of the two-dimensional bar code symbol.

CCD Readers. Charge coupled device (CCD) reading technology (Fig. 12.1.8) is the technology that has been most often associated with such devices as video cameras and for machine vision applications. CCD readers capture an image of the symbol and use it as the basis for decoding. The symbol is flooded with light and the resultant image is optically transferred to an image detector. The detector converts the photons it receives into electronic signals, organizes them into binary representations of pixels, and sends this data to a host system for decoding. The image detector can contain a single row of photodiodes or can have multiple rows of photodiodes, in which case the entire image is captured at once. CCD readers are available both as handheld or fixed-mount devices. For the handheld readers, distance from reader to symbol is limited typically to within a two-inch depth.

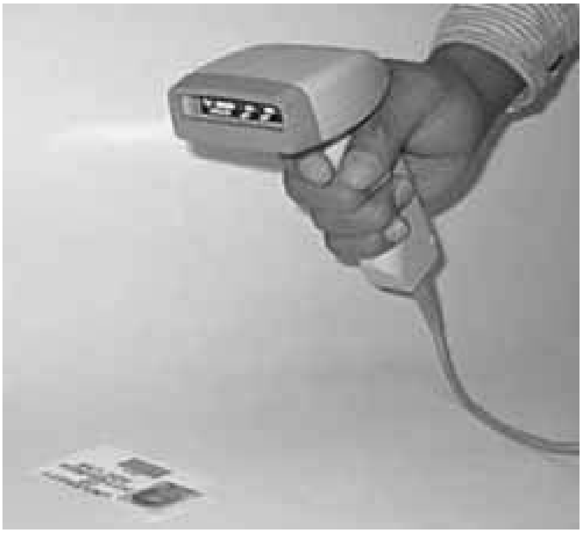

FIGURE 12.1.8 CCD reader.

Bar Code Printing

There are two major categories of bar code printing—*off-site* printing and *on-site* printing. Off-site printing is used to reproduce bar code symbols for subsequent use. It is used when there is a need for a large volume of identical or sequenced symbols. Off-site printing of symbols is completed by a commercial printing vendor for future usage on products. Two of the most common off-site printing techniques are *flexography* and *photocomposition.* On-site printing is used to create symbols at the time and place they are used. For this reason, it is often termed *demand* printing. At the time of this writing, the four most common demand printing technologies are *thermal, thermal transfer, laser,* and *ink jet.*

Direct Thermal Printing. Direct thermal printing makes use of a coated substrate, usually a paper label, that turns to a dark color, usually black, when subjected to heat. The image is created by a chemical reaction of the coating, caused by the application of the heat. The heating is caused by a thermal printhead that is in direct contact with the thermally sensitive coated label. The most common type of printhead is the fixed head, which contains a linear array of rectangular heater elements. This configuration incorporates approximately 320 rectangular dots, each measuring approximately 0.254 mm (0.010″) square.

Thermal printing is popular for bar code use because of its flexibility in printing bar code symbols, graphics, and human-readable characters. It is also known for its high-image-quality features. However, there are several disadvantages to thermal printing. Because the labels are sensitive to ultraviolet light and temperature extremes, thermal printers are recommended for indoor applications only. In addition, these labels tend to easily smear. Therefore, they should not be used in harsh environments where the symbols may come into direct contact with other objects. Finally, because the printhead is in direct contact with the label, the printheads tend to wear and must be regularly replaced.

Thermal Transfer Printing. Thermal transfer printing is the most widespread demand printing technique for bar code symbol generation. These printers have several of the same characteristics as thermal printers, such as the usage of a thermal printhead and label stock. However, the printhead does not come into direct contact with the label. Rather, a special ribbon is placed between the printhead and the label. The printhead applies heat to the ribbon, which then releases its pigment onto the substrate to create the image.

Thermal transfer printing has the same advantages of thermal printing without the disadvantages. Current printheads exceed 400 dots per inch, allowing quality bar code symbols to be printed with close tolerances. Because plain paper is used for the labels, the symbols do not easily smear and are not impacted by ultraviolet light. In addition, the printhead has a longer life than those used with thermal printers.

Laser Printing. With a laser printer, an optical image is transferred to a photosensitive surface by a controllable laser beam. The photosensitive surface is typically a rotating drum. The electrostatically charged image on the drum then passes over a toner station, where toner particles are attracted to the charged area. The toned image is then transferred onto the paper substrate. Laser printing has the capability to produce high-quality symbols due to the high dot per inch (dpi) resolution available with this technology. Current office laser printers print at or above 600 dpi.

Due to the high resolution of a laser printer, this technology normally prints a high-quality bar code symbol. However, when using laser technology for printing bar code symbols, the user should be aware of the potential for bar growth or bar shrinkage. These problems occur when there is a mismatch between the available printer dpi and the choice of the X dimension (the narrowest bar or space element in the symbol). For example, if a 600 dpi laser printer is used to produce a bar code symbol with an X dimension of 0.279 mm (0.011″), then 6.6 dots will be required to produce a bar with this X dimension. As a dot is indivisible on a laser printer, then the print driver will attempt to scale the image by either truncating to 6 dots or by rounding to 7 dots. The impact on the symbol is either unplanned shrinkage or growth of the bar's X dimension, producing a poor-quality symbol that may not be successfully scanned.

Many of today's bar code printing software packages have corrected the bar growth/shrinkage problem; however, the knowledgeable user should still take care to choose an X dimension that is an equal multiple number of dots. In the previous example, an X dimension of 0.254 mm (0.010″) would create a bar with an X dimension 6 dots wide and thus would eliminate any possibility of bar growth/shrinkage for this particular laser printer.

Ink Jet (Bubble Jet) Printing. Ink-jet printing is fast becoming the predominant printing choice for office environments. The improvements in resolution, ability to print in multiple colors, and low cost of these printers all contribute to its increased usage. Ink-jet technology works by heating ink that is resident in a cartridge (Fig. 12.1.9). The cartridge is sealed except for a small nozzle opening at one end. As the ink reaches a certain threshold temperature, some of it begins to vaporize, causing increased pressure in the cartridge. To relieve the pressure, the liquid ink is forced through the open end of the cartridge onto the substrate material.

For bar code symbol printing, ink-jet technology holds vast opportunity for the reasons just cited. However, the technology is not without its drawbacks. Because ink-jet technology is a dot-based technology, like lasers, it has the same potential problems for bar growth, so a match must be made between selection of an X dimension and the resolution of the printer.

An additional potential problem is ink spread. Unlike laser technology, where toner adheres to the substrate to create the image, ink used for ink-jet technology is absorbed by the substrate. This absorption can cause the ink to spread in an unpredictable manner. As a result, based on the physical properties of the substrate, the ink spread may cause the bars to grow,

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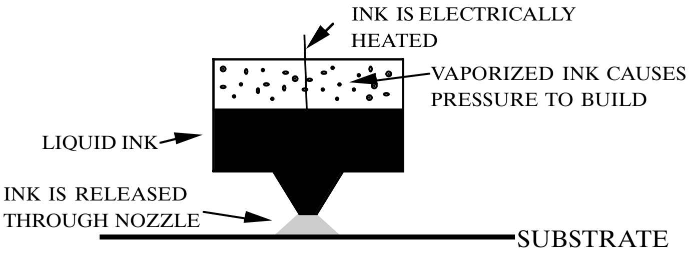
INK IS ELECTRICALLY HEATED
VAPORIZED INK CAUSES PRESSURE TO BUILD
LIQUID INK
INK IS RELEASED THROUGH NOZZLE
SUBSTRATE

FIGURE 12.1.9 Ink-jet printing.

and necessarily, the spaces to shrink, causing possible tolerance problems with the symbol. To avoid this problem, care should be taken when selecting the substrate for printing bar code symbols with ink-jet printers. Paper with low absorption properties should be considered. Fast-drying inks will also tend to minimize this problem. Proper testing of the selected papers should be done before releasing the application to a production environment.

TWO-DIMENSIONAL BAR CODE DATA COLLECTION

There are a growing number of applications where it is more desirable to use a disposable, portable, optically-based data file associated with an object than it is to access a remote database for information about that object. This is the case, for example, in such industries as distribution, in which trading partners must share common information but do not share databases; or energy, in which material safety data sheets on containers of chemical material must be tracked.

To meet this need, ADC manufacturers have developed a new breed of bar code symbologies termed *two-dimensional* (2D) symbologies. These new symbologies have higher character capacities and are more space efficient than traditional linear bar codes. Two-dimensional symbols are proving to be a durable and inexpensive way to encode considerable amounts of information in a relatively small area [3].

3.1 Structure

The overriding objective of a 2D symbol is to encode the largest amount of machine-readable information in the smallest possible area. To meet this objective, the basic structure of a symbology can be placed into two major categories—*stacked* codes and *matrix* codes. In stacked code symbologies, data characters are encoded in a linear fashion utilizing multiple rows. The symbol is often printed in a rectangular shape to obtain the most efficient use of label area. Each row contains a module of the total encoded data. Each row is scanned in a linear path, but all rows must be scanned for a successful decode. Each row is also uniquely identified so that the entire message can be correctly decoded when scanned in any order. Stacked symbologies can be scanned with conventional scanners configured with the proper software. These include *laser* scanners, *linear CCD* scanners, and *matrix CCD* scanners [4].

Matrix codes are array-based symbologies. They resemble a checkerboard pattern and are often square in shape. Matrix codes are a visual representation of machine executable electronic binary code. The binary code is formulated as a matrix having a perimeter border or a center target area with data contained within the area of the border. The perimeter border or center circular target area indicate the density, size, and orientation of the matrix. Rather than depending on varying element widths as in linear bar codes, matrix-code-based symbologies are read by determining the color (black or white) at the center of each cell [5].

BAR CODES AND OTHER AUTOMATED DATA COLLECTION METHODS

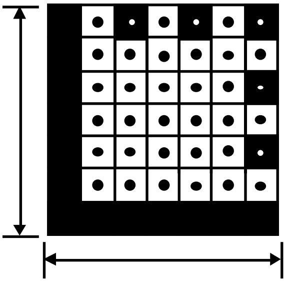

FIGURE 12.1.10 Determining orientation, density, and size of Data Matrix symbol.

For example, Fig. 12.1.10 illustrates the structure of Data Matrix, a popular matrix symbology. Data Matrix has a perimeter border comprised of two solid sides. The remaining border has sides comprised of alternating light and dark cells. The orientation of the symbol can be deduced by measuring the two solid sides of the symbol and calculating its angle. The density of the symbol is determined by counting alternating light and dark cells along the remaining perimeter. Color is determined by dividing the size of the solid border by this cell count. This resulting value is used to locate cell centers, which are then interrogated for light or dark color.

Matrix symbologies rely exclusively on CCD technology for reading. This technology is what allows for the omnidirectional scanning capability of matrix symbologies. Matrix symbol scanners evaluate data from a two-dimensional area, locating each element in both x and y coordinates simultaneously.

Two-dimensional bar codes have several special features required of many applications that cannot be addressed by traditional linear bar codes. These features include high data capacities, error correction capabilities, ability to be decoded from any orientation, and edge independence.

2D Symbology Standards

Many 2D symbologies have been introduced into the marketplace over the last few years. At the time of this writing, over two dozen different 2D symbologies exist, with new ones being introduced every year. It is not possible to give a detailed discussion of all of the symbologies. Following is a description of those symbologies that have been recently accepted as standards.

PDF417. PDF417 (Fig. 12.1.11) was introduced by Symbol Technologies in 1991. It is best classified as a stacked symbology, although it is commonly referred to as a *portable data file* because of its high data capacity of 1850 alphanumeric characters or 2710 numeric digits. The basic data unit is called a *codeword.* A codeword is a numerical value representing the encoding of two alphanumeric characters. Codewords can take on values in the range from 0 to 928 [4].

FIGURE 12.1.11 PDF417 symbol.

Any PDF417 symbol is made up of at least 3 rows, and at most 90 rows. The minimum number of codewords in a row is three, which includes the left row indicator codeword, one data codeword, and the right row indicator. To help the scanner keep track of which row is being read, different rows in a PDF417 symbol use repeating clusters of different mathematical formulas for encoding data. PDF417 has two error detection check digits and error correction capabilities. Error correction is selectable among eight levels.

PDF417 is being accepted as a standard for many handheld scanning applications where symbol size is of less importance. It has been accepted by the ANSI MH10.8–SBC–8 commit-

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tee for shipping and receiving and electronic data interchange (EDI) [6]. It has broad-based support by such organizations as the American Association of Motor Vehicles (AAMVA), Department of Defense, and the Automotive Industry Action Group (AIAG). Recent widespread applications include incorporation of PDF417 symbols on all U.S. armed forces personnel identification cards and on the driver license renewal applications for most Department of Motor Vehicles divisions. Other industry trade organizations are recommending to their respective memberships that PDF417 be used for such applications as quality conveyance, warranty claims, production evidence, production broadcast, configuration management, and material safety data sheets.

Data Matrix. Data Matrix (Fig. 12.1.12) is a matrix symbology developed by ID Matrix. Data Matrix is based on a checkerboard arrangement of black and white squares. This symbology has a perimeter border along two sides of the symbol used to determine the location, size, and orientation of the symbol. Up to 500 characters can be encoded on a single symbol. Data Matrix has encryption capabilities allowing it to be used for security applications. Because Data Matrix symbols can be printed in sizes as small as 0.254 mm (0.001″), they are ideal for small-component marking applications. In addition, because they use CCD technology for scanning, they can be read with symbol color contrast as low as 20 percent. Data Matrix was recently recommended by the Electronics Industry Association (EIA) as the symbology of choice for small-component marking applications such as printed circuit boards and electrical components. Two SEMI standards have been drafted recommending Data Matrix for silicon wafer identification and as the label for silicon wafer boxes.

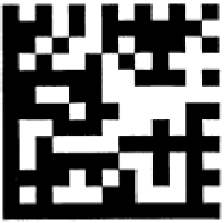

FIGURE 12.1.12 A Data Matrix symbol.

MaxiCode. MaxiCode (Fig. 12.1.13) is a matrix symbology developed by United Parcel Service for automatic sortation and tracking of transport packages via high-speed conveyors and fixed overhead scanners. MaxiCode was recently selected as a standard by the SBC-8 Committee for high-speed sortation and tracking applications. This symbology consists of a one-inch square array of interlocking hexagons that surround a circular pattern. The circular pattern is used for identifying the location and orientation of the symbol. The hexagons may be black, white, or gray. MaxiCode has a maximum capacity of 92 characters. Major features of MaxiCode are that it can be read at very fast conveyor speeds (approaching 500 feet per minute) and can be scanned at high rates, and the fixed reader system has an autofocus capability that can scan packages of different sizes. Laboratory tests have shown that MaxiCode symbols can be read at the rate of 14 symbols per second, and that the system can reliably read symbols on packages that vary in height from 1 to 36 inches [7,8].

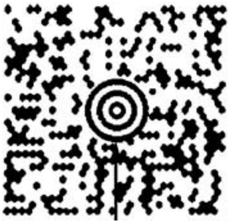

FIGURE 12.1.13 A MaxiCode symbol.

Choosing a 2D Symbology

Those contemplating 2D applications should begin their research by checking the status of various standards. Several industry groups have selected or are in the process of selecting two-dimensional application standards. These groups not only select a particular 2D symbology but often define a standard coding structure to help prevent manufacturers from labeling the same product several different ways.

In addition, the status of the symbology standard itself should be checked. Products in the public domain that can be employed without restriction are often the best choice. Public domain symbologies let users purchase system components from a wide variety of suppliers. The potential user of a 2D symbology should check to ensure that multivendor support is available.

In trying to decide between a matrix symbology and a stacked symbology, several issues must be addressed. If the space requirements for the symbol are limited, requiring a symbol smaller than one inch, then a matrix symbology such as Data Matrix may best be employed. However, if space limitations are within the two- to four-inch range, than a stacked symbology could easily be employed. For most handheld scanning applications, stacked symbologies such as PDF417 are most often adopted. This is due to the flexibility offered through the raster laser technology commonly available with stacked symbologies. For automated sortation and tracking applications, a matrix symbology such as MaxiCode with its high read rates is best employed.

WIRELESS DATA COLLECTION

One of the fastest-growing segments of the ADC industry is *wireless data collection.* Wireless data collection is another member of the family of radio frequency (RF) technologies that include radio, TV, radar, and microwaves. Wireless data collection refers to systems that communicate data over radio link between a host computer and a data source such as keyboards, data terminals, readers for Optical Character Recognition, bar codes, magnetic stripes, radio frequency identification tags, and so forth. Wireless data collection enhances the capabilities of wired communications without the restrictions of interconnecting wires.

There are two major categories of wireless data collection technology currently in use in industrial settings: *radio frequency data communications* (RFDC) and *radio frequency identification* (RFID). RFDC systems use portable interactive bar code readers. Once a scan is made on a bar code symbol, the information is sent back to a host computer via a radio signal. RFDC systems are useful in warehouses for picking and placing items stored on shelves. In manufacturing, they are used for receiving and shipping materials and products. RFDC systems are often used in the retail industry for tracking items on display or on shelves.

RFID systems use a radio signal to retrieve data stored in a small electronic device attached to the item being tracked. This technology is an alternative to systems such as bar codes which do not work properly in environments where labels may become dirty, painted, or damaged, or when the distance impedes a proper reading. RFID systems have three main components: (1) reader, (2) antenna, and (3) tags. The reader interrogates the tag by means of a radio wave signal sent by the antenna. The tag sends another signal with the information requested. This signal is captured by the antenna and read by the reader. The information stored in the tag may be an identification number, or routing/transaction information. Innovative applications of RFID technology have been developed to solve identification problems and to improve productivity. Much development effort has been expended to use RFID systems to track shipping containers on high-speed sortation/tracking conveyor systems. They are sometimes used for tracking automobile parts in assembly lines; for access control to restricted areas; and in libraries and stores to minimize shoplifting. Recent innovative uses of this technology have been for tracking patients in an emergency room of a hospital, and recording race car finish times.

There are a number of reasons why wireless data collection might be preferable to more traditional data communications systems. These include portability where the terminal is brought directly to the item, ease of creation and lower expense due to the elimination of wiring and its associated costs, avoidance of prohibitions that would make wiring infeasible (e.g., spanning a river), and added capabilities such as worker paging, locator functions, and the ability to receive data as well as send data.

RFDC Systems

System Operation. RFDC systems are made up of a number of components, as illustrated in Fig. 12.1.14. A typical system consists of a host computer, an intermediate terminal server or network controller unit, an RF signal transmitter/receiver (also known as a *radio base station, application point,* or *transceiver*), and portable, remote terminals. Such a system works in the following way:

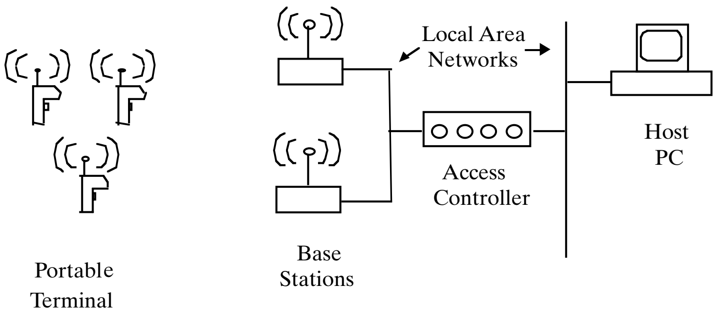

FIGURE 12.1.14 Typical RFDC configuration.

1. Data is electronically captured via a portable terminal.
2. The data is converted to a radio signal and then transmitted on a specific radio frequency.
3. The base station receives the signal, converts it to a digital format, and sends it to the intermediate terminal.
4. The intermediate terminal relays the message to the host computer using the network controller.
5. The host runs the program that manipulates the database and controls the remote terminals.
6. The reverse path is used to return information to the remote units.

RF Communication Frequencies. Wireless communications between the remote terminals and the base station comprise the main benefit of an RFDC system. This link is the radio signal; and the entire system depends on this connection. The use of the radio spectrum is controlled by governments of all countries. Different portions of the spectrum are reserved for different applications, with the overall goal being to manage usage and applications in such a way as to minimize disruptions and interference. In the United States, control is maintained by the FCC (Federal Communications Commission), which not only controls the assignment of frequencies but also the amount of power that can be used to generate a signal.

Successful installation of an RFDC system requires careful consideration as to the types and sources of interference that will be encountered. Interference can be addressed by either avoiding it or ignoring it. To this end, two major classes of RFDC devices have been developed: narrow band and spread spectrum. Table 12.1.2 summarizes these two types of RFDC technologies [9–12].

Narrow-Band RFDC. Narrow-band (NB) RFDC was the first communication methodology employed in RFDC. The allocated NB frequency ranges from 450 to 470 MHz. The FCC

TABLE 12.1.2 Comparison of Spread Spectrum and Narrow-Band RF

	Spread spectrum	Narrow band UHF
Frequency range	902–928 Mhz 2400–2483 Mhz 5600–5783 Mhz	450–470 Mhz
Maximum power	1 W	2W
Bandwidth	26 Mhz, 83 Mhz	2 Mhz
Channel width	Entire	25 KHz
Data rates	Up to 11 Mbps	Up to 9600 bps
License required?	No	Yes
Bandwidth sharing?	Similar and dissimilar equipment. No fixed channels	Similar equipment, fixed channels

formed a policy to assure that people who wanted to use RFDC would be able to do so without fear of disrupting others also wishing to use such technology. To this end, the FCC required narrow band RFDC users to obtain a license giving them the exclusive use of a particular frequency within a defined geographic area. Because the range of these systems is quite large (up to 10 miles), the bandwidth was restricted to just 25 Khz, thus allowing more devices to be operated within the same geographic area. Licenses are still required to operate narrow band RFDC equipment.

This restriction in bandwidth of course affects the effective data transmission rate of narrow band RFDC, limiting it to just 9600 bps, and correspondingly limiting the number of transactions per second that can be generated and sent to a base station.

Spread Spectrum RFDC. Although narrow band RFDC is still in use, the majority of RFDC devices in use today incorporate spread spectrum (SS) technology. In response to the demand for a greater number of channels and the need for a technology that produced higher data throughput, in 1985 the FCC allowed for L-band data communications in the 902 to 928 MHz range. Recently, this policy has expanded, allowing RFDC transmission in the 2400 to 2483 Mhz range. A third band in the 5-Ghz range is available but not currently in use.

In spread spectrum RFDC, the amount of power available for transmission is limited, reducing the effective transmission range of each device and thereby enabling the FCC to dispense with the need to require licensing. Users are allowed access to the entire bandwidth, thus enabling much higher data transmission rates than previously realized. The baud rates can exceed 200,000 bps, over 20 times the maximum NB baud rate. As a result of high spread spectrum transfer rates, the possible number of remote terminals served by each base station is increased. Thus, an offshoot of SS is to allow the use of a larger number of remote terminals.

However, there is a tradeoff in using a spread spectrum system. The physics of radio transmission dictate that the combination of faster data transmission, higher frequencies, and lower allowed output power reduce the range of signal transmission to less than 500 feet in any direction. However, total coverage can be enhanced through repeaters that receive and retransmit the signal.

Understandably, because different users can now be colocated within the same geographic area, a problem arises if two or more users attempt to transmit in the same bandwidth at the same time. To alleviate this problem, the FCC requires that, in addition to a low power output (maximum of 1 watt), spread spectrum RFDC devices employ either some methodology to avoid interference from other users, or insulate their systems by making them immune to others' transmissions. *Frequency hopping* is the technology that enables the system to avoid other users, while *direct sequence* allows the user to ignore or tolerate interference from other users.

FREQUENCY HOPPING: The purpose of frequency hopping is to avoid sources of interference by transmitting for short periods of time on a large number of channels within an overall allocated bandwidth. Figure 12.1.15 illustrates a typical frequency hopping scheme.

The wide-band spectrum is divided into a number of smaller bands, with small dead zones called guard bands placed between each channel. These guard bands ensure that transmissions will not overlap into adjacent channels and cause interference. Any number of channels

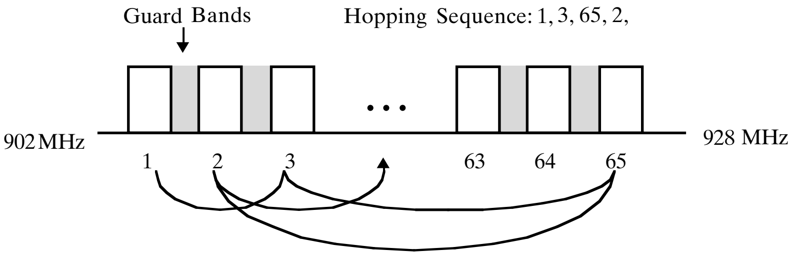

FIGURE 12.1.15 Frequency hopping.

can be used, as long as there are at least 50. Typically, more channels than are necessary are used so that if a recurring persistent source of interference is identified, it can be locked out of the hopping sequence without affecting overall transmission parameters. Hops are made between channels in a pseudo-random fashion, with the next channel being selected by a hopping code generator. To further ensure that all users have an equal chance at using the same frequency, the amount of time a system is allowed to stay or *dwell* on a channel is limited. Typically, systems are allowed to dwell no more than 0.4 seconds per channel before moving to another one.

Because the entire premise of this scheme lies on using a large number of small discrete channels to transmit data, the effective data transmission rate is considerably less than that of one using the entire allocated bandwidth all at once. Data transmission can be thought of as a closed system, with all the parameters inextricably linked. Increasing one parameter will, by definition, lower some other in order to keep the system in equilibrium. Frequency-hopping spectrum systems are limited in their data transmission rates by the size and number of channels that they employ.

DIRECT SEQUENCE: In contrast to frequency hopping, which tries to avoid interference by using small parts of the spectrum for short periods of time, direct sequence uses a large part of the assigned spectrum as a single channel, then attempts to ignore the interference. Figure 12.1.16 illustrates this process.

A primary bandwidth of a relatively large size (for example, 26 Mhz) is selected for use in transmitting data. Alternate bandwidths are also identified in case the primary bandwidth has too much interference to be usable. A bit to be transmitted is first redundantly encoded via the use of a *spreading code.* The makeup of this code is arbitrary, but it is always at least 10 bits long and consists of a predetermined series of 1s and 0s. The bit to be transmitted is then subjected to Exclusive OR arithmetic with each bit in the spreading code. The resulting bits are called *chips* (to differentiate them from the original bits).

The resulting string of chips is transmitted, where the process is then reversed. The chip set is decoded with Exclusive OR arithmetic using the same spreading code that was used to encode the bit, and the resulting string is examined. If the bits are the same, then the data is

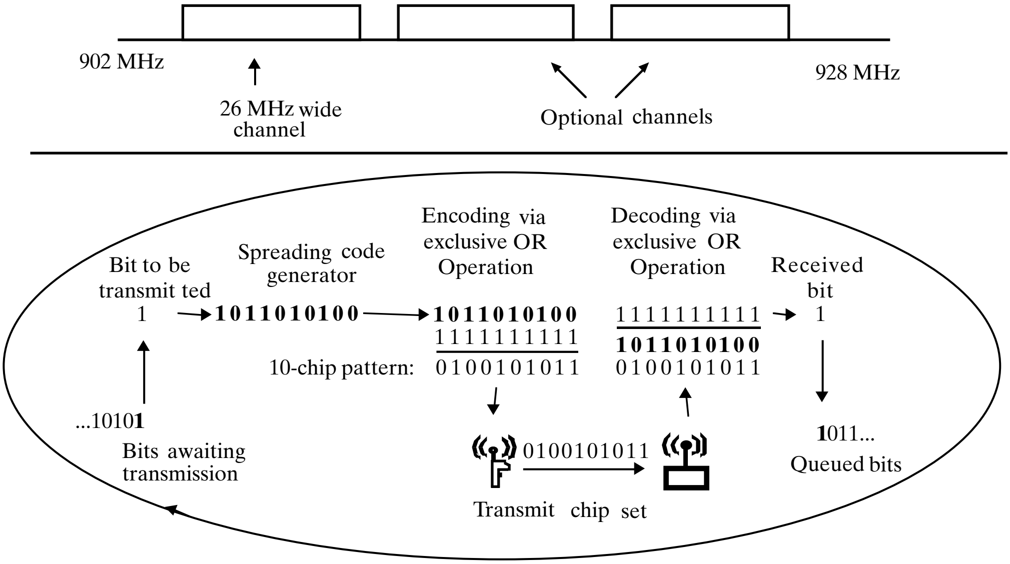
902 MHz
26 MHz wide channel
Optional channels
928 MHz
Bit to be transmit ted
1
Spreading code generator
1011010100
Encoding via exclusive OR Operation
1011010100
1111111111
10-chip pattern:
0100101011
Decoding via exclusive OR Operation
1111111111
1011010100
0100101011
Received bit
1
...10101
Bits awaiting transmission
0100101011
Transmit chip set
1011...
Queued bits

FIGURE 12.1.16 Direct sequence.

considered to be successfully sent and is queued in a buffer, where it awaits appending to prior and/or subsequent bits sent. The cycle is repeated until the entire message has been sent.

Direct sequence takes advantage of the fact that an increased channel size (i.e., bandwidth) allows a higher effective data transmission rate. Immunity to noise and corruption is achieved by redundantly sending each bit (upwards of 10 times, depending on the size of the spreading code). However, because information is being transmitted multiple times, the net effect is a reduction in the overall efficiency of the transmission. The sheer size of the direct sequence bandwidth as compared to narrow-band or frequency-hopping transmission, however, means that even with redundant transmission of data, it is able to achieve a much higher effective transmission rate than may be accomplished with either of the other two technologies.

RFDC System Design and Implementation

Using RFDC is a matter of applying technology to solving business problems. Once a decision has been made to utilize RFDC, there are important factors to consider in designing and selecting a specific system to match the particulars of the commercial application. The trick is to match the system design to the requirements of the problem, with an eye towards cost and future goals. A model of the proposed system should be constructed with consideration given to each of the following factors:

1. *Type of environment.* RFDC transmits data via an intangible shared medium, and behaves similarly to a network. As such, each element in the system is affected by other elements in the system, and there is a possibility of interference from external sources. At best, response time will increase with additional terminals; at worst, a critical failure may halt the system.

2. *Type of data collection being done.* RFDC systems should only be used when the benefits of real-time, portable data collection are genuinely needed. In general, RFDC systems have lower data rates than their wired counterparts.

3. *Type of terminal/equipment.* Having decided that RFDC is appropriate, consideration needs to be given to the type of terminal that will be used. Normally, this entails a choice between handheld or vehicle-mounted terminals. Optional features may also need to be considered, such as keyboard layout, size of display, and so forth. In addition, some terminals are "smart," giving the user limited on-board processing capabilities, thus reducing the amount of radio traffic that needs to be generated. Terminals should also be powerful enough to operate for a full shift under normal usage conditions without replacement or recharging of batteries.

4. *Ancillary equipment.* Most RFDC systems interact in some fashion with bar codes. Will the system under consideration handle multiple symbologies? Will it interface with equipment such as printers?

5. *Radio technology/Legal requirements.* Spread spectrum technology, although newer than narrow band, is not necessarily better. The choice should be made only after a careful analysis of all pertinent factors. Is a site license able to be obtained to use a narrow-band system? What kind of throughputs are needed? How big is the area to be covered, and what kind of obstructions and interference can be expected?

6. *Site surveys.* The unique characteristics of a facility—such as large electric motors, narrow aisles, large metal racks, close proximity to other RFDC systems and so forth—all have an effect on how well an RFDC system will operate, and some such factors can cause effective transmission ranges to be reduced by orders of magnitude. An initial site survey is needed to establish levels, types, and locations of interference. It is also used to establish the viability of providing radio coverage for the desired area, and establishing locations for base units.

7. *Application analysis.* Assuming the application in question requires real-time portable data communications, other typical questions that must be identified and answered include:

- What types of data will be transmitted, and what will they be used for?
- Will data be scanned or entered via keyboard?
- Will the terminal display be used to display data, instructions, or both?
- Who will operate the terminals, and how computer literate are they?
- Is the function in question already being done somewhere?
- Does more than one application need to be supported?
- What system response time (i.e., performance standard) is needed?
- How long can the system be out of service if a fault occurs?

8. *Connectivity.* Does the system under consideration utilize an open-system architecture, allowing it to connect with multiple environments, or is it stand-alone and proprietary? The simplest systems utilize standard data packet protocols such as RS232 or RS422.

9. *Software.* Applications for the RFDC system are typically written in one of two fashions: (1) an application-specific piece of software is written for a host computer with a corresponding terminal emulation program for the RF terminal, or (2) the application-specific program is written for both the host and the RF terminal. The first approach has the advantage of simplicity and flexibility. There is no need to specifically match a particular terminal to either a host computer or program; interface routines make connectivity transparent. Distributing the program's functionality between host and terminal, however, allows the full programmability of the terminal to be realized. Such things as onboard processing and transaction verification can result in more efficient use of the radio link, and thus in faster overall system performance.

10. *Installation and acceptance.* This can be done by the supplier of the equipment, by a knowledgeable third party, or by the company itself. Agreement on responsibilities must also be defined, and acceptance tests determined to ensure that the system operates as expected.

11. *Training and support.* The appropriate level of training needed to support the system must be determined as early as possible so that unnecessary delays are avoided. Training may be as simple as a five-minute get-acquainted session, or more formalized vendor-initiated lessons on hardware, software, and maintenance of the system. Particularly complex systems may require ongoing training, especially in the case of upgrades or new additions to the current system.

12. *Maintenance.* Various levels of maintenance need to be considered. At the simplest level, items like replacement or recharging of batteries must be addressed. Can generic replacement parts be purchased or are all parts vendor specific? At a higher level is confirmation of item performance and identification of faulty devices. Are there built-in self-diagnostics available, or a means of connecting remotely to a host for fault analysis?

OTHER ADC TECHNOLOGIES

Pen-based Systems

Pen-based systems are handheld, portable data collection systems. These products make use of a touch-sensitive screen for data input (Fig. 12.1.17). This technology is receiving increasing widespread usage across many different industries. Pen-based computers are best used when paper-based forms are replaced with electronic forms. The portability of these systems allows the user to be mobile while completing the electronic form. Typical applications include updating patient charts as physicians perform rounds, completing parking citations, filling in package delivery forms, field inspection, and recording quality-control information.

When attempting to make a choice of a pen-based system, criteria such as hardware size, weight, speed, battery technology and life, cost, and screen technology and resolution are typically considered. However, a critical factor in selection is the ergonomic *feel* of using the device.

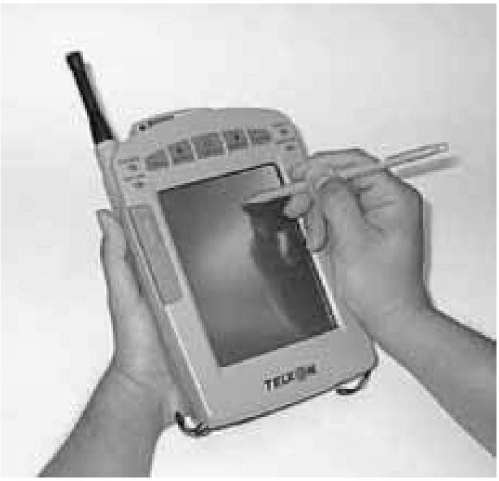

FIGURE 12.1.17 Pen-based system.

Chip Cards

Chip cards are a member of the smart card family of ADC products. Chip cards (and smart cards in general) are plastic cards similar in appearance to credit cards, with a computer chip embedded into them. Chip cards are memory-only cards that employ an EPROM (Erasable Programmable Read Only Memory) chip within their structure. These cards are used primarily in Europe for communications and banking. Their most widespread application is in prepaid phone cards. Rather than the telephone user dialing in a series of identifying numbers, chip cards are placed in a slot reader located in the telephone. The chip is then electronically activated by the phone, automating the dialing sequence. Currently, approximately 60 percent of the French population use either chip cards or smart cards on a daily basis.

Contact Memory Buttons

Contact memory buttons are physical devices directly attached to an object (Fig. 12.1.18). These devices are read by direct physical contact with a reading device. The buttons themselves are small stainless steel containers, the size of a small button, with a memory chip sealed inside. The buttons have the ability to read or write data through momentary passive or active contact. Contact memory buttons are typically used in harsh environments. They are sealed to resist moisture, temperature extremes, and radiation. Typical applications have included access control, animal tracking, and tracking of physical assets such as fire extinguishers, gas cylinders, or pallets.

Automatic Speech Recognition

Automatic speech recognition (ACR) systems operate by digitizing a person's vocal track. Stochastic modeling techniques are then employed to match a person's spoken words and

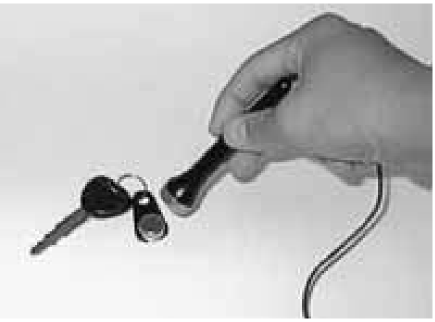

FIGURE 12.1.18 Contact memory.

phrases with the stored digital representation of those words and phrases. ASR is best employed for those applications where a user must have his or her hands or eyes free to perform some given task. Examples of recent applications include the automatic generation of work measurement standards where a user can speak into a portable ASR system while concurrently observing work in motion; automatic recording of defects while performing visual inspections through a microscope on hundreds of microelectronic chips; making airline reservations on the telephone; and the overcoming of learning disabilities (such as dyslexia) by performing homework assignments through speech to text-dictation systems.

FUTURE TRENDS

Like most high-technology industries, the ADC industry is rapidly changing, offering new and improved products as quickly as technology can be developed. In this final section we will describe likely products and trends that are appearing in the marketplace at the time of this writing. These can be summarized as improvements to bar coding, increases in wireless applications, and increases in chip and smart card applications.

Bar Code Industry

Permanent Bar Codes. Users of material tracking systems in many industries such as metalworking and plastics have a strong need for a permanent bar code symbol engraved directly into the metal or plastic of their products. Steel manufacturers and their customers—those industries that form steel and other alloys into fabricated products—need a symbol that can withstand harsh environments. Typically, metal-worked products must undergo operations in their process that expose them to temperature extremes commonly above 2000 degrees Fahrenheit, and they are often dipped in caustic acids and solvents. Obviously, a bar code symbol printed onto a paper label is inappropriate for these harsh environments.

To this end, much research has been done to engrave a permanent mark onto the metal or plastic product. So-called *bumpy* bar codes have been recently introduced into the marketplace in an attempt to provide such a permanent bar code symbol on a product. CNC engraving, laser etching, and cast molding have all been used for this purpose. However, these technologies are either expensive or not very flexible. Recently, *dot peening* has been used to create a permanent symbol on a product. This low-cost solution is an impact method for imprinting a bar code symbol onto a metal part. A series of dots are sequentially pounded into the metal object, one row at a time (similar to dot matrix printing), until the bar code elements are fully created. CCD technology is required to read dot-peened and other bumpy bar code technologies.

Direct Marking. In conjunction with permanent marking, there will be increased research to improve direct marking capabilities for bar code symbols. Labels are expensive and labor-intensive to apply. Much research is being done to improve ink jet technologies so that a bar code symbol can be directly applied in automated conveyor applications such as in shipping departments. Direct marking applications eliminate the extra costs associated with labels and thermal transfer ribbons.

Smaller Bar Code Element Widths. As bar code printing and scanning technologies continue to improve, the X dimensions of bar code symbols will continue to shrink in size. Currently, most scanners typically read a symbol with an element width as small as 0.178 mm (0.007″). However, some 2D symbologies can currently be printed at the microscopic level and read by fixed-mount CCD camera technology. As the bar code element widths shrink with improved printing and scanning technology, the advantage is that symbols will be smaller and able to encode much more information than what is currently practical. This will serve to significantly increase the number of applications for bar codes.

Increased Usage of Two-Dimensional Bar Codes. Two-dimensional symbologies will never make linear bar codes obsolete. For most data collection applications, linear bar code symbols printed on label stock and containing a short data string provide a scanning solution that cannot be improved upon by a 2D symbol. However, applications that require greater data capacities than is currently available with linear bar codes will probably utilize 2D bar codes. Applications that require identification of very small items in manufacturing environments; sortation and tracking of items in high-speed automatic conveying systems; and scanning portable, machine-readable data files and documents such as bills of lading or shipment manifests with approximately 500 to 2000 characters to be printed in a less-than 2-inch label will most likely employ 2D bar code technology in the near future.

Smart Card Industry

There will be increased usage of smart cards and chip cards in the future. In fact, many people believe that smart cards will eventually replace magnetic stripe cards for most personal identification ADC applications. Currently, standards are being developed for smart card technologies that will help to integrate the usage of these products into a much larger number of applications. Improvements in semiconductor technology will enable smart cards to carry increasing amounts of information. The chip card technology for prepaid phone cards that has swept Europe will ultimately reach the United States.

Wireless Industry

The ADC technology that is likely to see the fastest and largest growth is wireless technology. RFDC and RFID have made vast improvements in their respective technologies in the last two years. With the introduction of frequency hopping systems in the 2.4 Ghz radio frequency range, and the continued increase in throughput rates, these technologies are more reliable than they have been at any previous time in history. In addition to portable terminals that are wireless, additional components such as transceivers, printers, and computers have recently been introduced as wireless. Improvements to RFDC and cellular technology will increase the usage of pen-based computer applications, palm-top computers, and automated speech recognition applications.

With RFID, the price of RF tags will continue to decrease so as to be comparable to bar codes. It is anticipated that this technology will eventually be utilized in the package delivery business, where high-speed sortation and tracking must be done; grocery checkout, where an entire basket of items may be checked out simultaneously by wheeling the grocery cart under an antenna; and in retail security to minimize shoplifting and theft.

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BIOGRAPHIES

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Bopaya Bidanda is the Ernest Roth Professor and chairman of the Department of Industrial Engineering at the University of Pittsburgh. He is also the codirector of the University's Manufacturing Assistance Center and the Automated Collection Laboratory. In addition to his doctoral degree from the Pennsylvania State University, he has industrial experience in manufacturing systems, tools, and precision manufacturing. His research focus includes the areas of computer-integrated manufacturing systems, robotic applications, industrial engineering, automated data collection, and shared manufacturing. He has published widely in international journals and conferences, and he has edited/authored two books: *Automated Factory* and *Shared Manufacturing*. He actively works with manufacturing industries in western Pennsylvania in the areas of cellular manufacturing, work measurement, data collection, and shop floor information systems. He is a senior member of the Institute of Industrial Engineers (IIE) and the Society of Manufacturing Engineers (SME). Dr. Bidanda currently serves as a director of the Pittsburgh Chapter of IIE. He was cochair of the Annual Industrial Engineering Conference for 1998 and 1999.

Martin Adickes is a senior systems consultant for Symbol Technologies, Inc. Dr. Adickes specializes in information systems and has extensive expertise in both theoretical and practical wireless data collection system design and implementation. Previously, Dr. Adickes worked as a senior research scientist for Battelle National Laboratories.

Source: MAYNARD'S INDUSTRIAL ENGINEERING HANDBOOK

ACHAPTER 12.2

MANAGEMENT OF DATA

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In today's economic climate, all manufacturers need to lower costs, reduce times for new products to reach the market, implement more effective management decision making, and generally improve efficiencies. To achieve these goals, more accurate and usable information and better systems for processing data are essential. In this chapter we will consider the application of information technology and structuring of the information and communication management systems that must handle information quickly and accurately on a daily basis, companywide.

The need for integrated, companywide systems is clear, but companies face many challenges in attempting to build such systems. Simply patching together the independent and incompatible systems that exist in manufacturing companies today will not provide the required capabilities. Inherent challenges are described, particularly in relation to information needed at each stage in the product development process, which has a particular demand for speed, accuracy, and coordination.

The innovations instituted at one manufacturer, which achieved a 40 percent increase in the efficiency in its overhead departments is discussed and the new concepts of early disposition, concurrent disposition, and managed information flow are introduced and explained.

The importance of improving information systems as a key component of thorough, companywide innovation and reengineering programs is stressed as an essential activity for manufacturers who plan to survive in the twenty-first century.

INFORMATION TRANSFER IN MANUFACTURING INDUSTRIES AND A PHILOSOPHY OF INFORMATION AND COMMUNICATION MANAGEMENT

Recently in manufacturing industries, there has been a trend toward dividing and separating the functions related to production. In most factories, today machinery is now of the numerical control (NC) type, and information related to the factory floor is processed by computers. However, we find that this information is not managed in an integrated, enterprisewide manner, and there is no system enabling all employees to use it. In particular, in product development and design departments, the engineers actually engaged in the development and design of a part may be so busy that they are unable to visit the factory floor. They develop a design based only on information and directions from their supervisors. They work without knowing much about the situation on the factory floor and without having design information about other products and parts. In addition, the situation is often such that even management may be unable to obtain the latest information.

As a result, the degree of "readiness for manufacture" of newly designed products seldom improves. Consequently, many design changes are required and deadlines for shipping are often missed. Or, if products are rushed to the market before they are finished, claims from unhappy customers are likely to occur, resulting in a negative impact on business. Thus, at present time, manufacturing is an environment in which the information necessary for production activities is not communicated in a timely and accurate fashion.

Overseas production facilities are becoming more common now, but in many cases information interchange between the parent company and the overseas factories is a significant problem. Of course, computer tools such as computer-aided design (CAD), computer-aided manufacturing (CAM), and electronic data interchange (EDI) are widely used, and with these systems, exchange of information can be accomplished in less than half a day. However, it is not possible to manufacture products that will satisfy customers and managers based only on digital information provided by these computer tools. This is because, for the product-making activities of manufacturing industries, generally two types of information must be transmitted in a mixed form: (1) explicit information such as drawings, and (2) tacitly understood information based on the know-how of individuals in various departments of the company. Information of these two types is mixed with communication and then conveyed using information tools, methods, and management systems that are not integrated and standardized throughout the company. All people, groups, and company departments communicate using a variety of tools, methods, and systems. Thus, it is not surprising that the level of understanding information varies widely throughout the company.

Presently the two most important issues are

1. How to convey the tacitly understood information based on the know-how of individuals in various departments of the company to all the other involved departments involved in a timely and concurrent manner
2. How to connect that information to all the key activities occurring in the company, including product development and design, prototype manufacturing, test, production engineering, and manufacturing

It is not an exaggeration to say that proper management of information and communication is indispensable for solving these problems.

TRENDS IN INFORMATION TECHNOLOGY IN MANUFACTURING

After the Industrial Revolution, the manufacturing industry has been earnestly pursuing mechanization and improving efficiency, primarily focused on factory operations. There are two basic flows in manufacturing: (1) the actual flow of physical objects, such as fabrication of parts, component assembly, and final product assembly, and (2) the flow of information that enables effortless control of the physical flow. Recently, the latter has received more attention, and as methods and tools for that purpose, management systems and the computer systems for implementing them have been developed in fields close to the factory floor. However, in the operation of actual companies, (1) information systems for business processing (such as for the control of production, parts, and costs) and CAD/CAM/CAE, and (2) information systems for management control (such as sales and customer control, human resources control, etc.) are being created independent of each other and do not connect well in practice.

Manufacturing businesses face many challenges, such as reducing the time for product development, cost cutting, designing unique products, and getting them to the market quickly.

All of these require rapid decision making; however, the present information management systems cannot support that because they are fragmented. Therefore, demands for integration of these information systems, to enable faster management decision making, are on the increase.

The technical information that is either an input or an output at each phase of the development/production process is shown in Fig. 12.2.1. Presently, over 50 percent of the methods for conveying this technical information involve transmission by paper or human hands. Recently, however, requests for information transfer by computers are coming from many frontline departments that interact with the factory floor. Until just five or six years ago, the cost of a computer system that would truly integrate all the necessary information was so high that these requests could not be met. Therefore, most companies gave up on creating integrated information systems, despite the strong demands. However, based on recent developments in information technology (IT), it is now possible to build integrated, or unified, information systems at a reasonable cost. This involves constructing intranets and extranets using Internet technology. Significant progress has been made from the older schemes that were centered around a host computer with the technical data related to production composed mainly of alphanumeric data. The systems today handle technical data including image data, digitized in new formats, which can be accessed by engineers and operators on a real-time basis through their desktop PCs.

More and more companies are realizing the importance of creating such integrated information systems. These companies have started to build information systems that both gather and distribute the necessary information. All engineers are provided with PC terminals, and Internet technology and groupware techniques are used extensively. In other words, through developments in IT, systems are now available that, while integrating technical information, enable each information user to gather or distribute information selectively according to his or her individual needs. Accumulation of technical information in the form that meets the needs of each user level in the company—such as individual, team, section, department, or entire company—can now be accomplished in a simple manner.

This trend is now strongly in motion and certainly will not slow down.

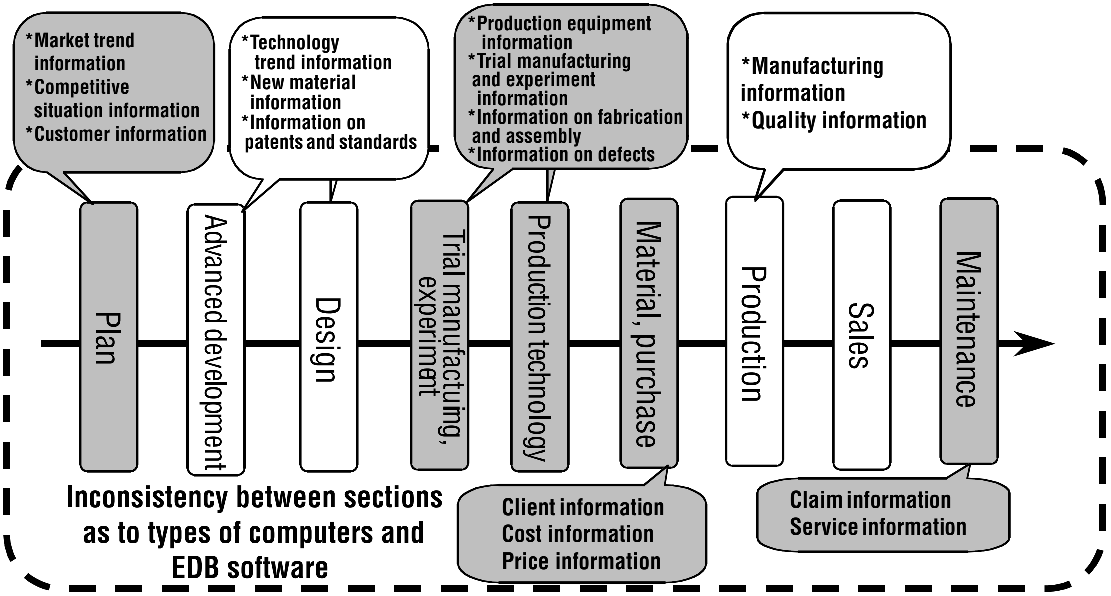
*Market trend information
*Competitive situation information
*Customer information
*Technology trend information
*New material information
*Information on patents and standards
*Production equipment information
*Trial manufacturing and experiment information
*Information on fabrication and assembly
*Information on defects
*Manufacturing information
*Quality information
Plan
Advanced development
Design
Trial manufactuimg, experiment
Production technology
Material, purchase
Production
Sales
Maintenance
Inconsistency between sections as to types of computers and EDB software
Client information
Cost information
Price information
Claim information
Service information

FIGURE 12.2.1 The development/production process and technical information.

CURRENT PRODUCT DATA MANAGEMENT PRACTICES IN MANUFACTURING COMPANIES

Product data management (PDM) systems will enable interaction between, and common use of, the information generated during the product-making process, from product conception and planning, to development and design, to preproduction, and eventually to production. In addition, these systems make it possible for employees to receive the information they need at the time and place it is needed, and thus can make effective use of it. The system permits the information needed at each stage of the process to be organized, accumulated in a consistent manner, and used effectively. This enables work to be done more efficiently and results in improved performance in quality, cost, and delivery (Q, C, D).

In recent years, computer makers have offered users various PDM systems and have also added development consultants to their staff system to assist their customers. The number of manufacturing companies taking advantage of such packaged systems and system development services is increasing. However, some manufacturers introduced systems with the naïve view that if they simply installed a PDM system they would immediately see results. This arose from the lack of knowledge on the part of the manufacturers and the intention of most computer makers to do business simply by selling hardware.

Figure 12.2.2 shows the structure of an integrated PDM system. This level of companywide systems is, however, not possible to achieve overnight. The general approach is to start with the existing individual systems in the company, and while taking advantage of the company's distinctive characteristics and strong points, build up an integrated system step-by-step.

With the general method of creating such systems, problems fall into three areas:

1. First, in an attempt to expand the system step-by-step, the areas of the company most likely to experience problems are the product design, development, and engineering departments. The typical output of these departments consists of drawings, bills of material, production orders, and so on, but generally these have already been converted to electronic data, using various computer systems. On the other hand, the information needed for the total process of product design may not yet be computerized, and that is a big problem. Business information, planning information, customer claim information, and information on market trends and the activities of other companies, for example, is not yet computerized. Instead, for conveying information of this type, companies still rely on conventional human media such as documents, voice, and images. Information of this type must be converted into electronic data and integrated into the total information system, and the extent to which a company can accomplish this will determine whether it succeeds in building an integrated, companywide PDM system.

2. The second problem is that in constructing an integrated PDM system, various techniques and specific knowledge are necessary, but for the most part, no individual engineer has mastered all the techniques and acquired the knowledge. The necessary techniques and knowledge are quite varied, as follows:

- Business process reconstruction techniques, such as reengineering
- Knowledge of PDM-packaged software programs
- Information technology disciplines
- Techniques for introducing and supporting PDM and IT
- Knowledge and techniques related to client/server systems and networks
- Internet knowledge and techniques, including intranets, and extranets
- Management techniques for incorporating IT into the business to form a well-integrated smoothly functioning organization

It is impossible for one person to master all these areas, and if management of manufacturing companies does not recognize this, it can be a major obstacle to building effective systems.

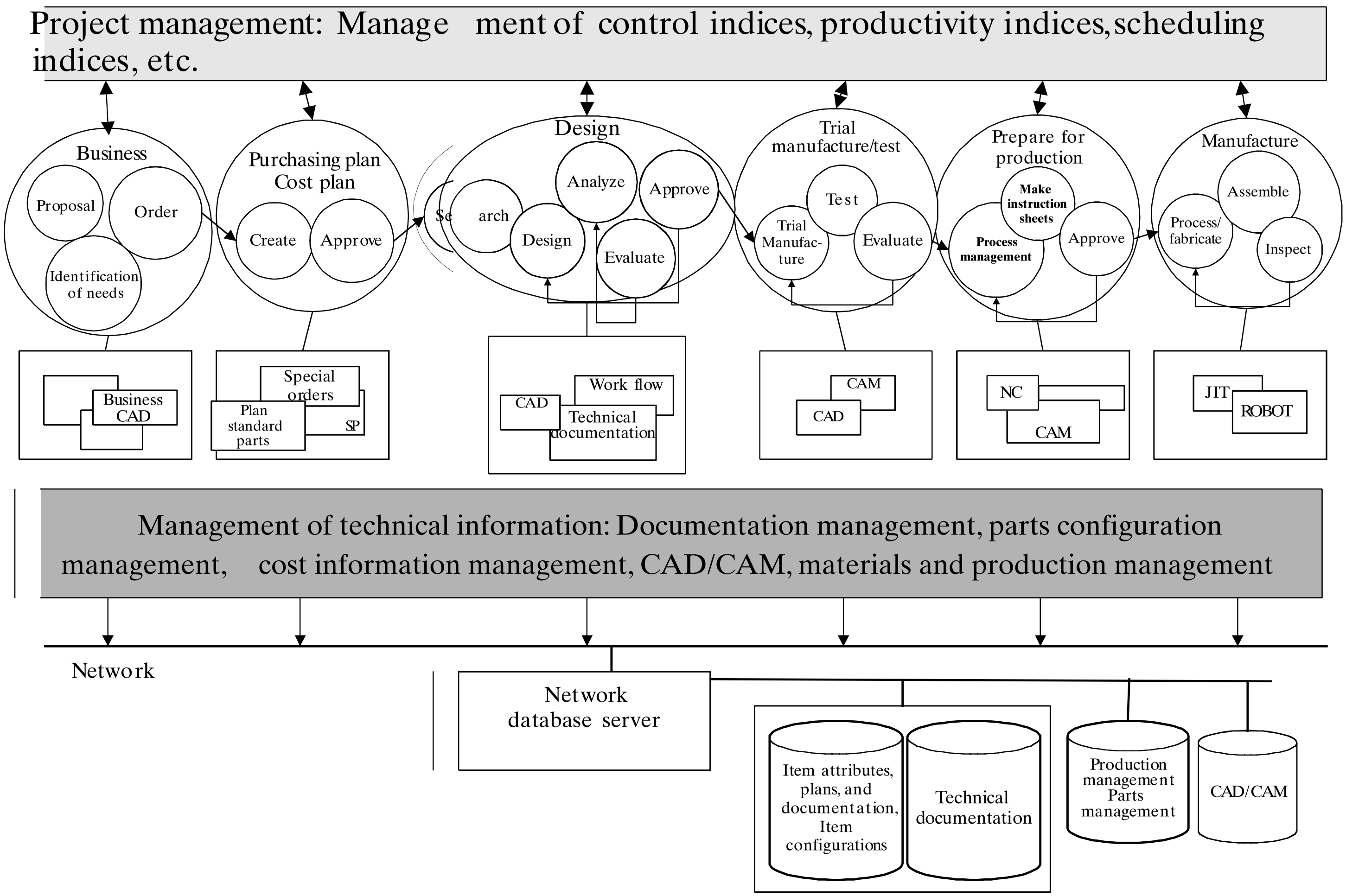
Project management: Manage ment of control indices, productivity indices, scheduling indices, etc.
Business
Proposal
Order
Identification of needs
Purchasing plan
Cost plan
Create
Approve
Design
Se arch
Design
Analyze
Evaluate
Approve
Trial manufacture/test
Trial Manufac-ture
Test
Evaluate
Prepare for production
Process management
Make instruction sheets
Approve
Manufacture
Process/ fabricate
Assemble
Inspect
Business CAD
Special orders
Plan standard parts
SP
CAD
Work flow
Technical documentation
CAM
CAD
NC
CAM
JIT
ROBOT
Management of technical information: Documentation management, parts configuration management, cost information management, CAD/CAM, materials and production management
Network
Network database server
Item attributes, plans, and documentation, Item configurations
Technical documentation
Production management Parts management
CAD/CAM

FIGURE 12.2.2 Structure of an integrated, companywide PDM system.

3. The third problem is that it takes too much time to achieve results. On the other hand, if the focus is on short-term results, the tendency is to build individual, unconnected systems, and this will limit the ability to achieve an integrated, companywide PDM system. Today there are only a few companies that use benchmarking to measure the cost-performance of integrated PDM systems, so evaluation methods have not yet become standardized and companies must rely on the judgment skills of their managers.

How well manufacturers proceed to solve these problems is key to successfully building integrated, companywide PDM systems—that work. Manufacturers who complete this important task quickly and effectively will survive in the twenty-first century.

MANAGING THE USE OF INFORMATION IN BUSINESS AND PRODUCT DEVELOPMENT PROCESSES

In the product development process and other business processes, the information necessary at each stage of the process arrives in the form of both vague (or abstract) information, such as opinions and estimates, and clear information such as data. This information is then processed and flows to the next stage. The information and communication management systems that control the passage of this information are critically important. At manufacturing companies today, how well such systems are made to function has a large influence on the level of perfection and market-worthiness of its products.

In the process of product making, information is generated first at the level of the customer and people near the customer. Then, at each stage—planning, advanced development, conceptual design, general design, detailed design, trial manufacturing, test and evaluation, preproduction, production, and sales—the information undergoes further processing and new information is added so that the volume of information increases. In the product development process, people at each stage of the process rely on this information as they perform their activities.

For products to be attractive in the market, they must be reasonably priced and must reach the market promptly and at the right time; otherwise, the company will lose out to competitors. The current market situation is such that if a product does not reach the market in at least second or third place, there is a good chance that it may never make a profit.

With the objective of creating a low-cost product in a short time and getting it to the market in a timely fashion, the "person in charge" must have the most accurate information available and must be empowered to take direct action based on that information. However, key judgments and decisions are made by company management, and usually, the path of information transmission connecting the person in charge and the company management is too thin. By the time the information reaches the company management, it is likely that the information will have been altered or distorted, which can create obstacles to smooth execution of the project. Broadening and speeding up this flow of vertical and horizontal communication through IT innovation is an essential condition for improving the product development process and other business processes.

In actual practice, the product development process and business processes activity is often conducted under conditions in which vague or abstract information and clear information are comingled. Today every manufacturer is beginning to recognize that clarifying or quantifying vague information can have a big impact on shortening development time and reducing costs in the product development process.

One method of quantifying such vague information is to simulate target values, such as time limits, in the product development process or other business processes. Recently this method has been implemented by leading manufacturers. In this way, an initial consensus among all parties, albeit tentative, can be obtained regarding target values and direction for each stage in a product development process (or other business process). The likelihood of achieving the targeted Q, C, D for product being developed then increases dramatically.

How to gather highly accurate information at stages close to the starting point of a project and process it in a way that supports the project is one key to competing effectively against rival companies. The second key is how accurately cross-functional actions can be taken based on such information. To achieve such effective information transfer, the role of information and communication management becomes very important (see Fig. 12.2.3).

INNOVATION PROGRAMS AND THE ROLE OF INFORMATION AND COMMUNICATION MANAGEMENT

Lately, business process reengineering (BPR) is being attempted in various kinds of companies. Effective use of IT can be a key factor in determining whether BPR programs succeed or fail. For example, at a certain manufacturer of metal-bending machinery, a three-year program to increase the efficiency of indirect (overhead) departments resulted in a 40 percent improvement. This program was undertaken in a direct, hands-on manner, with emphasis on the following four activities:

1. Computerization/mechanization/systematization
2. Control techniques and improvement activities
3. Skill improvement for both individuals and teams
4. Structural changes

The main factor in the program's success was that each overhead department, aiming at improvement and innovation in both the product development process and other business processes, sought innovations in the following areas, and explored each one thoroughly:

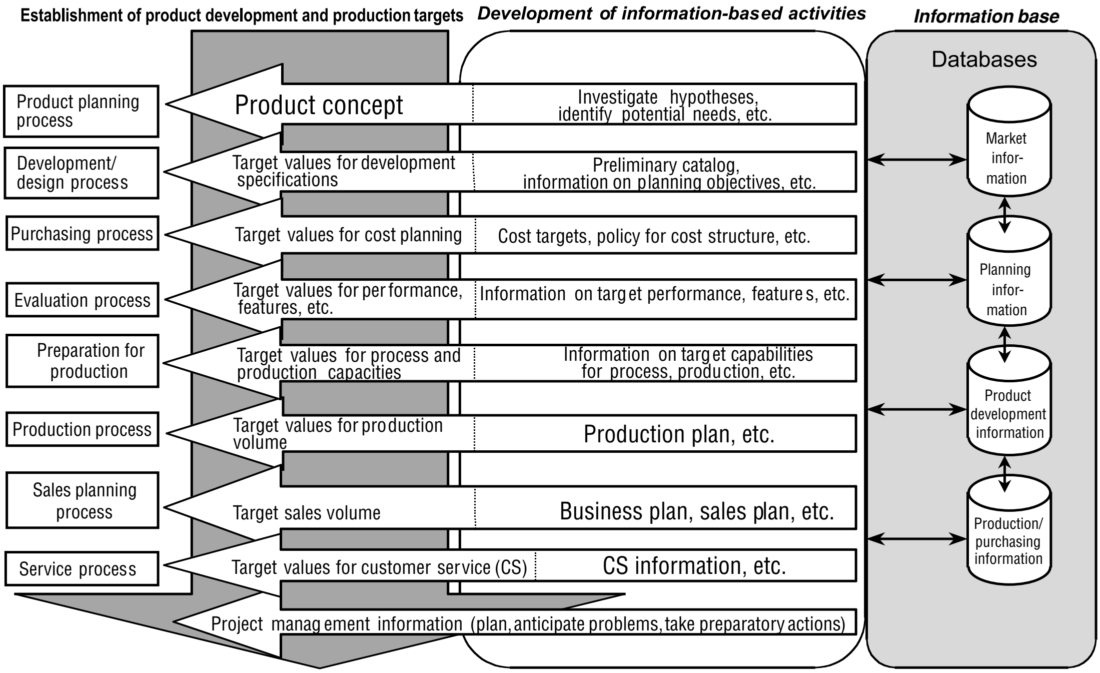
Establishment of product development and production targets
Development of information-based activities
Information base
Databases
Product planning process
Development/ design process
Purchasing process
Evaluation process
Preparation for production
Production process
Sales planning process
Service process
Product concept
Target values for development specifications
Target values for cost planning
Target values for performance, features, etc.
Target values for process and production capacities
Target values for production volume
Target sales volume
Target values for customer service (CS)
Investigate hypotheses, identify potential needs, etc.
Preliminary catalog, information on planning objectives, etc.
Cost targets, policy for cost structure, etc.
Information on target performance, features, etc.
Information on target capabilities for process, production, etc.
Production plan, etc.
Business plan, sales plan, etc.
CS information, etc.
Project management information (plan, anticipate problems, take preparatory actions)
Market infor- mation
Planning infor- mation
Product development information
Production/ purchasing information

FIGURE 12.2.3 Building information and communication management systems.

- Business innovation and process reforms
- Self-directed innovation at all levels of the workforce, and management innovation
- Structural reforms of the organization, and organizational innovation
- IT system innovation, including more effective data management

In all cases, the aggressive use of information technology, particularly IT system development, and the creation of effective information and communication management systems can be significant contributors to the success of the program.

How exactly are information technology and information and communication management involved in business innovation activities? To answer this, we will consider the product development process—the most important company activity for manufacturers—and will specifically examine the technique of concurrent engineering (CE).

In the product development process, CE is the technique of managing the information needed for product making by applying the approaches of early disposition, concurrent disposition, and managed information flow. The objective is to achieve the highest possible degree of completion at each process stage as quickly as possible. This is done across all process steps, from planning, to advanced development, conceptual design, general design, detailed design, trial manufacturing, test and evaluation, preproduction, production, and finally, sales.

Early disposition is the discipline of changing from a pattern of coping with problems after they have occurred to one of anticipating problems and taking action before they occur. *Concurrent disposition* is the approach whereby several company departments or divisions work cooperatively so that a plurality of functions can be accomplished concurrently and efficiently. *Managed information flow* aims at preventing delays in information flow and provides processes, system, and tools to enable information and matters requiring decision making to flow smoothly.

When the total product development process is considered from the IT standpoint, it is clear that the technique of CE is necessary in each intermediate process, including product planning, development/design, costing, quality assurance, and production processes. The relationship of these elements is shown in diagram form in Fig. 12.2.4. Technical information for product making as it occurs in the product development process is multifaceted, and the abil-

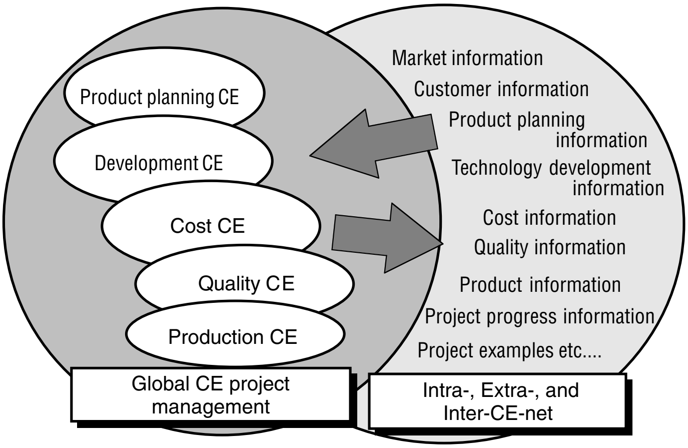
Product planning CE
Development CE
Cost CE
Quality CE
Production CE
Global CE project management
Market information
Customer information
Product planning information
Technology development information
Cost information
Quality information
Product information
Project progress information
Project examples etc....
Intra-, Extra-, and Inter-CE-net

FIGURE 12.2.4 The relationship between CE and technical information for product manufacturing.

ity to manage this information is demanded of today's project managers. It is clear that manufacturers cannot survive in the twenty-first century, unless they build the kind of companywide integrated systems described previously.

In any case, companies need to reform their business now, and to further such business reform they need to think about how to put information to practical use and manage it—by employing IT techniques effectively. In this context, how to organically connect the concrete plans and measures for business reform to information and communication management systems is an important subject for management.

For a manufacturer to create a solid plan and then take action according to it, is, in effect, building the base for enterprisewide innovation. Information technology and, for actual operations, information and communication management are the keys to success of company renewal.

Manufacturers must launch a variety of plans and measures for companywide renewal. Then, information and communication management systems must be skillfully integrated into these so that the successful modernization necessary to survive as a modern-day manufacturer can be accomplished.

BIOGRAPHY

Takayuki Mizuno is a senior consultant with JMA Consultants, Tokyo, Japan. He graduated from the Japan Electronic Engineering Institute, School of Software Engineering in 1970. For over 20 years he has worked in the field of computer systems and their effective utilization. He is particularly experienced in the application of computer systems and software in the environment of automobile R&D, design, prototyping, and manufacturing. Mizuno has designed, budgeted, and introduced both mainframe and PC systems and has trained users in their effective utilization. His consulting work has included the development and use of CAD, CAM, and EDB software, and the design and implementation of local area networks (LANs). He currently focuses on new technologies for systems integration and developing improved techniques of project management.

Source: MAYNARD'S INDUSTRIAL ENGINEERING HANDBOOK

CHAPTER 12.3

INFORMATION NETWORK APPLICATIONS

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The use and generation of information is pervasive in every industrial enterprise. The goal of using information is to support the production of goods and services within an enterprise. An important criterion for implementing effective applications is the adding of value to the product or service. In this chapter, we discuss the role of information in enterprise activities as well as current and future trends in applications. Databases that warehouse enterprise information play a central role in the dissemination of information. Network applications must be integrated with these databases and other applications to provide the necessary functionality.

INTRODUCTION

Information is a body of knowledge obtained through the collection and transformation of data. It is widely recognized that the generation and effective use of information is critical to the overall success of any enterprise. The trend of modern information systems is to make information more accessible to end users while at the same time ensuring the integrity and security of the information.

Most industrial engineers are very familiar with the concept of material handling in the context of manufacturing systems. The goal of effective material handling is to make material available for production at the point of use when it is needed. Material handling is considered to be a non-value-added process (with respect to the product), because no value is added to the product during the actual process of delivering the material.

We can take a similar view when we examine the role of information in an organization enterprise. In the same way that material handling is a non-value-added operation, the delivery of information to an operator, engineer, or manager provides no value with respect to the information. The value added to the information is found in the conclusions, decisions, and resulting operations that are derived from the information, or transformations producing new information that can be used somewhere in the process.

Adding value is a key attribute of useful information network applications. The value added in these applications comes from the algorithms implemented in the software. Applications that merely display raw data are not adding value. This is not to say that the viewer does not find the display useful. In much the same manner as assemblers require material to perform an operation, they may also need information to complete an operation. The ultimate goal remains to add value to a product or service. One of the most important considerations in using applications is whether value is being added, or whether time and resources are being consumed needlessly. The generation of new but meaningless information is undesirable. These types of applications can be self-perpetuating. They have a life of their own. They consume resources. They consume attention and often are distractions from the real problems facing an organization.

The material-handling system would correspond to the network infrastructure within an enterprise. This would include the hardware and software necessary to facilitate communications between the various computational devices as well as applications running on these devices. Networks make information available to multiple users. Ethernet [1] has become a de facto standard due to its widespread use in multiple organizations. Other network protocols are implemented due to special requirements or proprietary constraints of vendors. This collection of network protocols is used to provide a mode of transporting information between a source and destination much like the material-handling device delivers material from storage to a manufacturing process.

Information network applications are the processes that operate on available information. For the product life cycle, these applications can be categorized into the areas of product definition, process definition, manufacturing system definition, operations, and distribution. Network applications are the value-adding operations performed on the information. Questions that should be addressed include, What value is being added by the application? What would be valuable to the end user? An obvious answer seems to be that valuable applications help users perform their jobs more effectively (i.e., make them more productive and increase the quality of the output).

ROLE OF INFORMATION IN INDUSTRIAL ENGINEERING

Before we examine information network applications for industrial engineering, let us examine the use and generation of information in the industrial engineering domain. Consider the process model using Integration Definition for Function Modeling [2] (IDEF0) for a typical manufacturing enterprise as shown in Fig. 12.3.1. The overall goal of the enterprise is to deliver products to customers. For those who are not familiar with IDEF0 models, these networks model the relationship between activities or processes within an organization. The boxes represent a process or activity as defined by a verb and an object. Directed arcs are used to show the relationship between activities, resources, constraints, inputs, and outputs. The directed arcs entering the left side of a box represent inputs that are transformed (through this process) into one or more outputs, indicated by directed arcs exiting the right side of the box. Arcs that enter the bottom of a box are the resources or mechanisms necessary to perform this transformation. The top of the box is used to show the constraints (e.g., specifications, schedule, or budget) for a process. The activity label is placed in the lower right corner of the box and is hierarchical in nature.

In reviewing the overall process of delivering a product we find that most industrial engineers have major responsibilities in activities 3 to 6. Therefore, our discussion will be limited to information network applications within those domains. This not to say that an industrial engineer will not be involved with other types of applications outside those domains as team involvement may necessitate interaction with other domains.

Process Definition Domain

The objective of the process definition domain is to produce specifications, computer code, tooling, and so forth, which are necessary to produce a product from a design specification. This activity is illustrated by the simplified IDEF0 model in Fig. 12.3.2.

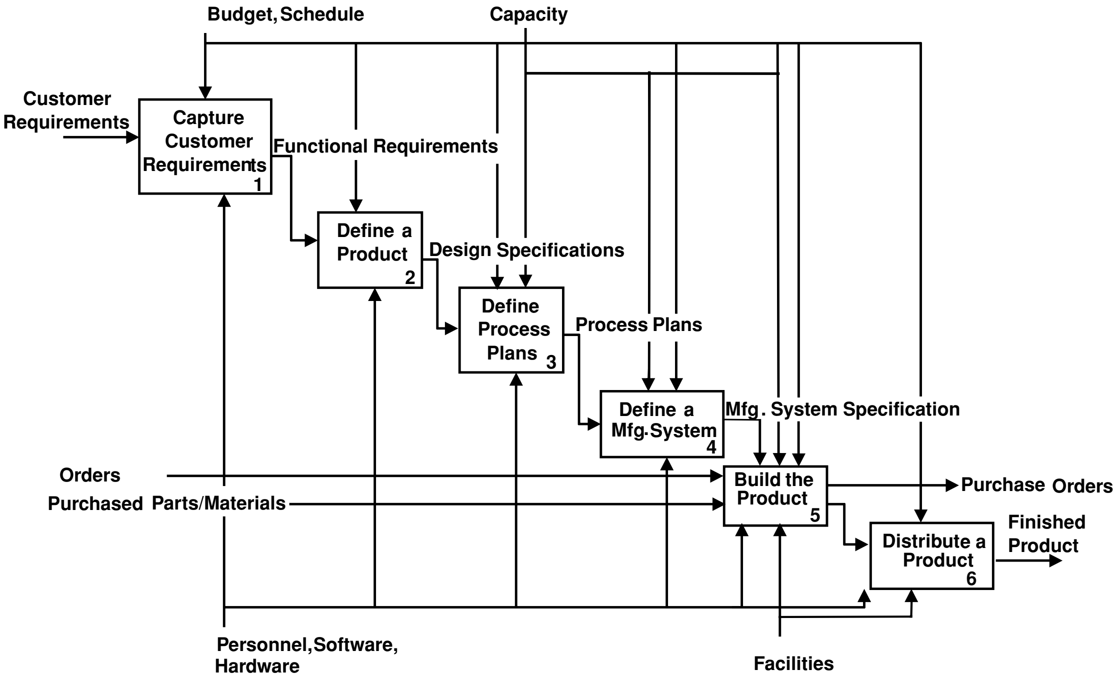

Budget, Schedule
Capacity
Customer Requirements
Capture Customer Requirements 1
Functional Requirements
Define a Product 2
Design Specifications
Define Process Plans 3
Process Plans
Define a Mfg. System 4
Mfg. System Specification
Orders
Purchased Parts/Materials
Build the Product 5
Purchase Orders
Distribute a Product 6
Finished Product
Personnel, Software, Hardware
Facilities

FIGURE 12.3.1 IDEF0 model for a manufacturing enterprise.

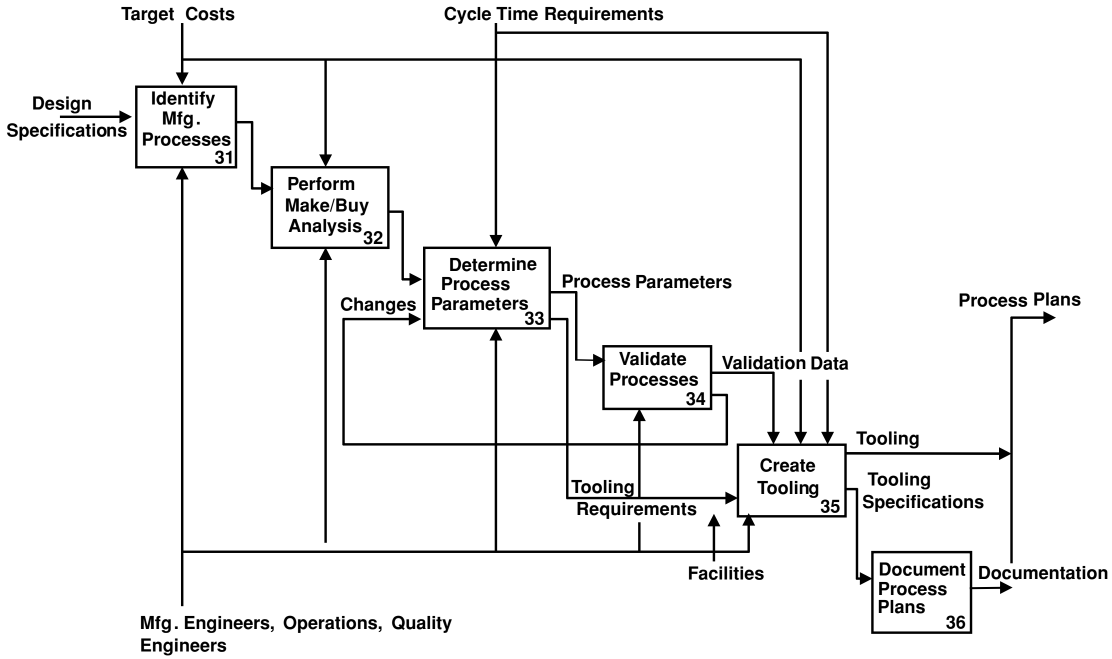

Target Costs
Cycle Time Requirements
Design Specifications
Identify Mfg. Processes 31
Perform Make/Buy Analysis 32
Determine Process Parameters 33
Changes
Process Parameters
Validate Processes 34
Validation Data
Process Plans
Tooling
Create Tooling 35
Tooling Requirements
Tooling Specifications
Facilities
Document Process Plans 36
Documentation
Mfg. Engineers, Operations, Quality Engineers

FIGURE 12.3.2 IDEF0 model for define process plans.

Given that the design specification is an input to this activity, it is clear that network applications must have access to product definition data to perform these activities. This interface between process planning and product definition has received increased attention recently [3]. However, there are numerous difficulties in making a smooth transition between product definition and the process plans. One of the most troublesome problems is the nature of the product definition process itself. A product is continuously evolving, undergoing numerous engineering design changes throughout its life cycle. These changes are the result of new product features, corrections of design flaws, and design improvements. The propagation of design changes through the process model of Fig. 12.3.1 spawns numerous activities to accommodate the changes. As a result, changes must be made in the process plans to account for changes in the design specifications. This is an iterative process that can require multiple passes as conflicts are resolved between the various activities.

Traditional applications extract geometry and part information from the design specification and bill of materials (BOM) to produce new information such as computer code for computer-controlled equipment. These applications typically require user interaction with the output (i.e., manual modification) in order to fine-tune the results. The lag time between design changes and process changes can be significant due to the need for validation (activity 34) and documentation (activity 36 in Fig. 12.3.2) of process plans.

Manufacturing Systems Domain

In the manufacturing systems domain we define and evaluate how the processes will interact in the system. At this stage the organization determines the rules for producing a product and how this will affect a manufacturing system. The typical activities in this domain are depicted in the IDEF0 model of Fig. 12.3.3.

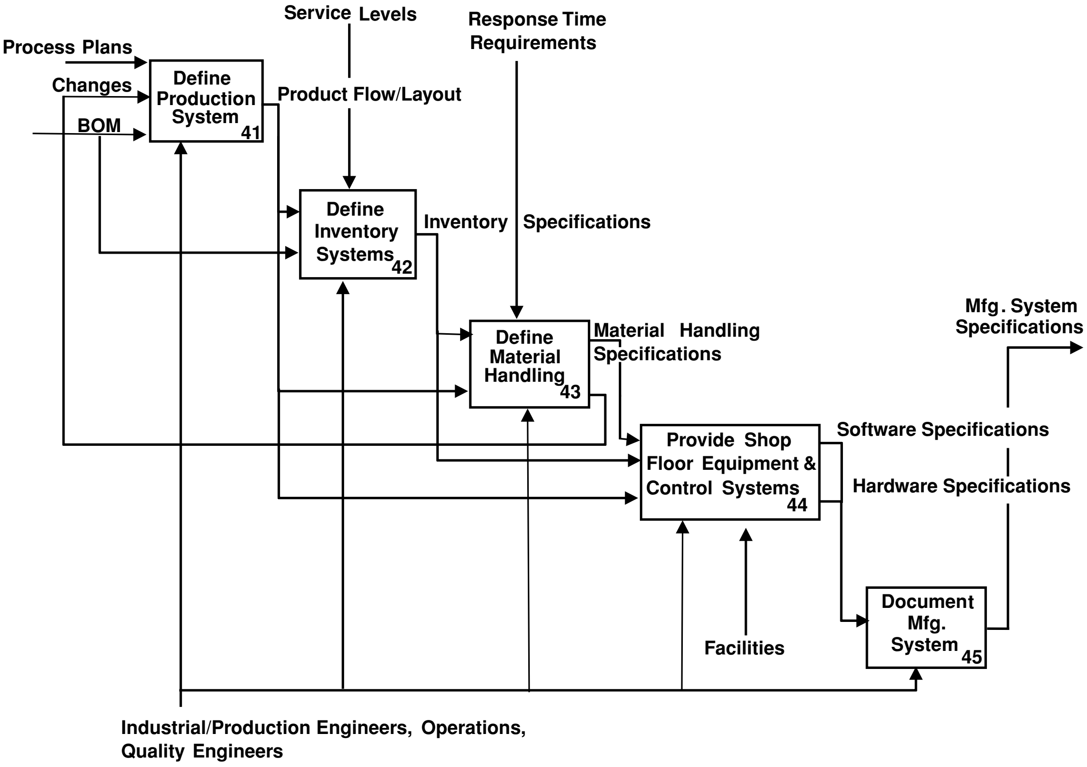
A production system configuration and strategy must be determined prior to production. This may require the development of an entirely new manufacturing system, or modifications of an existing system. As changes occur in process plans (an input to these activities), the manufacturing system specification must be revisited to determine what adjustments may be necessary. For example, if a new supplier has been added, we may have to change our inventory policies and storage systems. Typical applications used to support these activities include simulation, scheduling, inventory, shop floor control, and data acquisition.

Operations Domain

A simple operations domain can be modeled as shown in Fig. 12.3.4. In this domain, we are concerned about the actual manufacture of products. When we reach this stage, the major problems begin to appear. In a perfect world, the operations should take place according to all the specifications derived from previous activities. The main concerns of this domain are work order release, schedules maintenance, and resources utilization. Of course, Murphy's law is always observed such that constant adjustments are necessary to meet production requirements. Common applications that support this domain include scheduling, inventory, shop floor control, data acquisition, work instructions, and machine control software.

Distribution Domain

In the distribution domain, finished orders are shipped to customer locations. To accomplish this, a distribution system must be defined that can support distribution to a dynamic customer base (see Fig. 12.3.5). The changing nature (in terms of volume and location) of the customer base creates significant challenges in this area. Recent work in supply chain management has tried to address some of these issues. This domain requires applications for


Service Levels
Response Time Requirements
Process Plans
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Define Production System 41
Product Flow/Layout
Define Inventory Systems 42
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Define Material Handling 43
Material Handling Specifications
Mfg. System Specifications
Provide Shop Floor Equipment & Control Systems 44
Software Specifications
Hardware Specifications
Facilities
Document Mfg. System 45
Industrial/Production Engineers, Operations, Quality Engineers

FIGURE 12.3.3 IDEF0 model for the manufacturing system domain.

monitoring the real-time status of work orders, performance evaluation of the supply chain, and product tracking systems. Applications that support supply chain management are beginning to emerge.

APPLICATIONS

While there are numerous applications both large and small in scope within these domains, this discussion is limited to significant practices and trends in network applications. Given the domains as described, the major applications that support these domains are product data management, manufacturing execution systems, and enterprise resource planning. These applications have significant overlap in functionality as well as data that create numerous conflicts between systems [4].

Product Data Management

As shown in the previous discussion, access to product data is essential for information network applications. In response to this need, the concept of product data management (PDM) systems has been developed [5]. PDM systems are also referred to as engineering data management or product information management systems. The intent is to capture design infor-

INFORMATION NETWORK APPLICATIONS

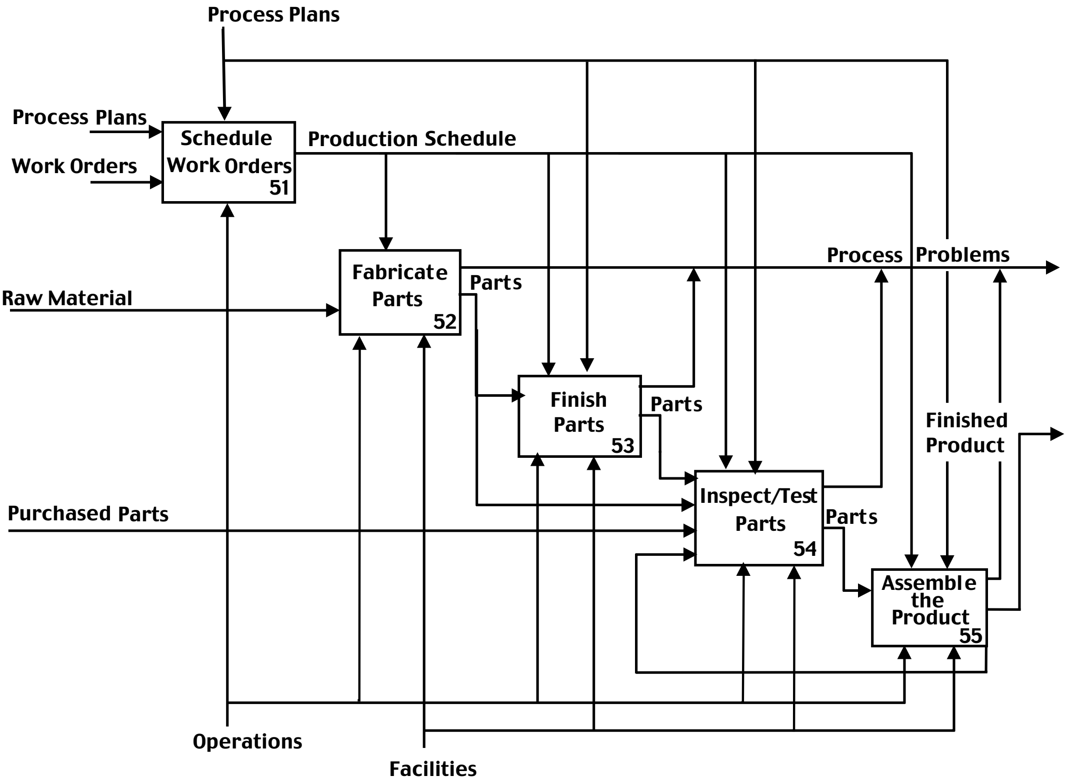
Process Plans
Process Plans
Work Orders
Schedule Work Orders 51
Production Schedule
Fabricate Parts 52
Parts
Raw Material
Process
Problems
Finish Parts 53
Parts
Finished Product
Inspect/Test Parts 54
Purchased Parts
Parts
Assemble the Product 55
Operations
Facilities

FIGURE 12.3.4 IDEF0 model for operations domain.

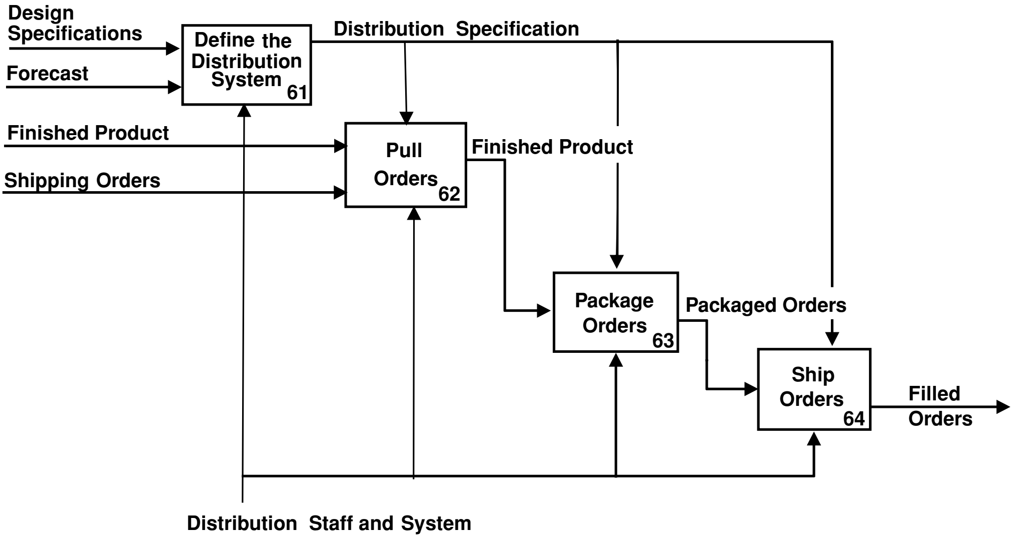
Design Specifications
Forecast
Define the Distribution System 61
Distribution Specification
Finished Product
Shipping Orders
Pull Orders 62
Finished Product
Package Orders 63
Packaged Orders
Ship Orders 64
Filled Orders
Distribution Staff and System

FIGURE 12.3.5 IDEF0 model for distribution domain.

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mation and control access by other users over the life cycle of the product. These systems play a major role in configuration management [6] applied to design. The concern here is to provide the *correct* design information to users. Here is an example of an application that provides no added value to the information. It merely behaves as a gatekeeper and data warehouse for the design information.

It has recently been recognized that a similar system (manufacturing data management) is necessary for manufacturing data created during the process definition domain [7].

Manufacturing Execution Systems

Manufacturing execution systems (MES) applications are still in their infancy. These applications are intended to schedule and control real-time operations within a facility. This would provide direct support for the operations domain as described earlier. The architecture for an MES is based on a database containing status information on the operations. Applications that access this database provide the necessary functionality to support the operations tasks. An MES is responsible for tracking work orders, collecting product and process data, allocating resources, and disseminating process plans [8].

Enterprise Resource Planning

Within the operations and distribution domains, it has been recognized that an integrated approach encompassing the needs of both areas is necessary. Enterprise resource planning (ERP) systems have been developed to address these domains. The major difference between an ERP and MES is that ERP systems tend to have a much larger scope for data and applications. This is because both domains share much of the same information in the performance of associated activities. One example of such a system is the SAP R/3 system [9]. As with other ERP systems, SAP is based on the construction and maintenance of a large database that represents a snapshot of the enterprise at a given point in time. Clearly, a database is not very useful without applications. ERP systems are configured by selecting a set of applications that can be customized for a particular enterprise. Typical applications include financial accounting, human resources, plant maintenance, production planning, quality management, supply chain management, and materials management.

INTEGRATION OF APPLICATIONS

The information technology industry has been in search of the Holy Grail for many years—the ability to have programs from different vendors communicate and work with each other—but there are many problems associated with this quest. The first problem is the large variety of operating systems and programming languages found in information systems today. Applications having interoperability often lose some functionality as they are ported to different platforms. The capability of sharing data can be completely different or nonexistent depending on the platform.

Integration projects can be subdivided into two main types, namely, application to database and interapplication integration. These integration solutions share a common approach of a client/server model. A client makes a request for certain information or functions from a server. A server responds by providing the information or performing the functions. Memory is reserved for the interface between two entities. All operations involve allocating reserved memory for the interface, placing data into the reserved memory for retrieving data, and releasing the reserved memory.

Database Integration

The first type of integration requires the capability of accessing one or more databases (possibly from different vendors). These applications usually retrieve information and perform some computation to transform the information into a different form. Another application could be transaction processing. One example of an integration tool is the Open Database Connectivity (ODBC) interface [10]. This interface provides a library of functions that support Structured Query Language (SQL) calls to databases from different vendors. The main steps in using ODBC is to set up a connection to a database server, send SQL statements, and receive the results of the transaction. Additional functions provide error handling. The following C code shows the fundamental process of using ODBC to retrieve data. Functions beginning with SQL are found in the ODBC library.

An ODBC Example

```
Void main()
{
//data representing the interface between client/server
HENV phEnvironment; //handle for memory
HDBC FAR* phDBC; //handle for connection
HSTMT phStatement; //handle for the statements

//set up the memory for the database connection
SQAllocEnv(&phEnvironment)

//reserve memory for the connection to the server
SQLAllocConnect(phEnvironment,&phDBC)

//make a connection between application and a server
//load driver and make a connection
SQLConnect(phDBC,source name,name length,user identifier, length
user identifier, user identifier, length user
identifier,password,password length);

//reserve memory for sending SQL statements
SQLAllocStmt(phDBC,&phStatement);
//place the SQL command in statement memory
SQLPrepare(phStatement,SQL text string, length of string);
//send the current statement in memory to the data source
SQLExecute(pHStatement);
//get the number of columns in the data returned
SQLNumResultCols(phStatement, &ncolumns);

//get information on a column
SQLDescribeCol(phStatement,column#,&column name,length of column
name memory,&actual length of name,&data type,&column
precision,&#digits to right of decimal point,&are NULL values
allowed);

// allocate memory for storing the results
SQLBindCol(phStatement,col#,data
type,pStorage,lengthStorage,&numBytesActual);

// read all the rows until the end of the column
while (SQLFetch(phStatement) != SQL_NO_DATA_FOUND)
{
look at pStorage for the results
perform processing
}

//release the reserved memory for passed statements
SQLFreeStmt(phStatement,SQL_DROP);
//break the connection to a data source
SQLDisconnect(phDBC);
// free reserve memory for the connection
SQLFreeConnect(phDBC)
// free up the memory used for the database connection
SQLFreeEnv(hEnvironment);
}
```

The future of interapplication integration may be based on the sharing of program functions or objects. This is the goal of initiatives such as Common Object Request Broker Architecture (CORBA) and Component Object Model (COM) from Microsoft. If programs are written using the COM architecture, then they can share functions with other programs using the same architecture. COM was originally developed for the Windows environment with the intention of extending it to other operating systems. Gates [11] suggests that COM provides the capability of communicating between applications. This will support the exchange of information from one application to the next. The basis of COM is a set of rules that programmer's must follow if they are going to share data between applications. Microsoft's Object Linking and Embedding (OLE) technology is an implementation of this approach.

CORBA Overview

CORBA, from the Object Management Group (OMG), has similar objectives [12] but uses a different approach. The OMG was established in 1989 and has over 500 members. The goal is to have a standard for interapplication sharing of information and functions. CORBA uses an Interface Definition Language (IDL) to support the transfer of information between programs that are written using different languages such as C, FORTRAN, or COBOL. By writing an interface to a program using IDL, the user can create an interface module in the programming language being used in the program. This module is compiled and linked with the program just like any other function. Typically, the IDL statements would be compiled with a native language compiler such as C or FORTRAN to create a *stub* that would be linked with an application and a *skeleton* that is simply the beginnings of a source code file that must be completed by the application developer. The stub and skeleton are key elements of the CORBA structure as shown in Fig. 12.3.6.

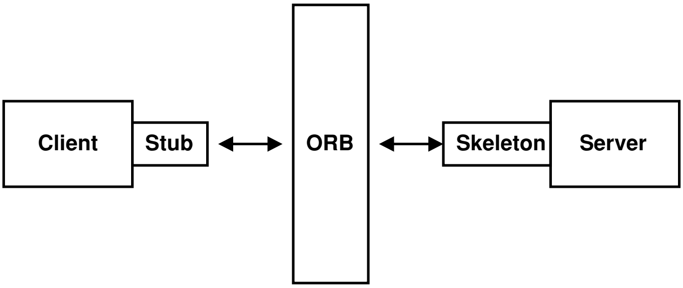

FIGURE 12.3.6 CORBA structure.

The CORBA interface consists of operations (i.e., functions), attributes (data), exceptions (errors). The functions are used to send and receive messages. Objects are accessed through a handle (i.e., a pointer). The IDL is used to specify the interface in a similar manner as the Class declaration in C++. Examples of the interface can be found in Ref. [13].

A CORBA Example

Consider the following IDL specification for an interface to a machine on the shop floor. The machine would have an application running that would respond to other applications according to the interface specification. In this interface there is data (the machine name) and operations (functions relating to machine operation). The operations return values through the interface that could also include error messages. The out, in, and inout specifiers in the argument list indicate the direction of information flow. For PositionStatus, the operation returns the current position of the tool in x, y, and z. The SetFeedRate is used to change the current feed rate on the machine by passing the new feed rate value. The Coolant operation is capable of both actuating the coolant valve and reading the status of the coolant valve.

```
interface Machine
{
char* name;
unsigned short PositionStatus(out x, out y, out z);
unsigned short SetFeedRate(in feedrate);
unsigned short Coolant(inout valve);
}
```

Another approach for implementing interfaces in CORBA is the Dynamic Invocation Interface (DII). This allows an application to find interfaces at runtime.

One of the inherent assumptions for interfaces is that they never change. If they do, stubs would have to be recompiled and source code may have to change to reflect these changes. Given the nature of the information environment, it would be safe to assume that interfaces will indeed change. The DII was created to accommodate changes. Essentially, applications look for objects at runtime and then request information on the interface.

The DII works by the client running a *create_request* operation (as shown) on an existing interface to create a Request object. The interface is first found by searching the interface repository (where interface definitions are registered). A data structure is then allocated representing this request and contains information about the interface. The client application writes argument values into the interface and then invokes operations.

```
create_request(in Context, in Identifier, in Arglist, inout
NamedValue, out pRequestObject, in flags); //sets up a request
```

The Request object is returned in pRequestObject. The Arglist is a list of operations to be performed by the object. When an operation is performed, the result is placed in NamedValue. The Request object has two operations that can be used to initiate operations on the object.

```
add_arg(in OperationName, in DataType, in Value, in Length, in
Flags);
```

This operation is used to set up the arguments (write to the Request object interface) for an operation specified by OperationName. For operations requiring multiple arguments, multiple calls must be made to this operation to complete the argument list. Once all the arguments have been specified, then the invoke operation is used to execute the operation.

```
invoke(in InvokeFlags) //executes the operation in the Request
object
```

COM Overview

COM has a similar mechanism for handling integration. The interface is described using the Interface Description Language. The file is compiled to create a stub and a template for the object. The stub is then linked with the application code. From a COM perspective (as shown in Fig. 12.3.7), an interface represents a set of functions. Each component can have one or more interfaces. The entire system consists of multiple components.

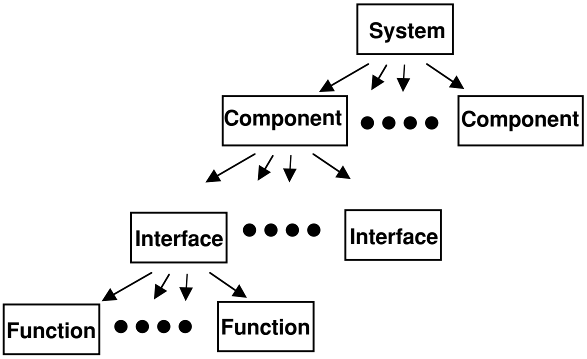

FIGURE 12.3.7 COM structure.

A COM Example

Consider the simple example of the machine interface described for CORBA. In COM (using C++), the interface might look like the following *interface* structure, which is used to specify the actual data structure for the interface.

```
interface IMachine //Machine interface
{
virtual unsigned short _stdcall PositionStatus(int* x,int*
y,int* z)=0;
virtual unsigned short _stdcall SetFeedRate(float feedrate)=0;
virtual unsigned short _stdcall Coolant(int* valve)=0;
};
```

The declaration of the component class includes the inheritance of the interface structure.

```
class CMachine : public Imachine
{
member declarations
method declarations
}
```

The functions corresponding to the interface are written for the component.

```
unsigned short CMachine::PositionStatus(int* x,int* y,int* z)
{
statements

}
unsigned short CMachine::SetFeedRate(float feedrate);
{
```

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```
statements

}
unsigned short CMachine::Coolant(int* valve);
{
statements
}
```

The code for the client application would have the following form.

```
void main()
{
CMachine* pM = new CMachine; //make an instance of this
component

IMachine* pIM = pM; //make a pointer to the interface

pIM->SetFeedRate(500.0); //use the interface

delete pM; //delete the component
}
```

Legacy Systems

Successful applications create a problem of legacy. After years of using a given application, a large volume of information is created that may have trouble being integrated into future systems. Complicating the matter is the expertise developed by users and software engineers. This familiarity and established knowledge base creates an inertia that prevents new applications from taking hold within the organization. When new applications are selected, major consideration must be given to addressing the current legacy system. Will information be converted to the current application? What will it take to perform the conversion? If we do not convert existing data, how will we deal with the legacy information? Will the new application be compatible with the previous system(s)? One of the approaches to ensure the survival of legacy data is the use of COM or CORBA interfaces for new applications. These interfaces can provide a mechanism to communicate with existing programs and databases.

Internet/Intranet

The Internet has a long history of providing a mechanism for sharing information. It is only in recent years that it has received widespread popularity. This is due mainly to the implementation of a supporting infrastructure popularly known as the World Wide Web. The basis of the infrastructure is hypertext [14]. This is essentially a sophisticated card file system. By associating links between locations in the text or graphics, a user can connect to other files (local or remote), applications, and programs. This approach is ideally suited for the dissemination and viewing of information. An intranet is no more than an internal network that only private members (such as employees of a company or subgroups within a company) can view. This allows the dissemination of information without letting the public see sensitive or proprietary information. Given the current infrastructure, applications discussed in previous sections have plans to provide interfaces to the Internet so that users can view data in a variety of forms and interact with programs at remote locations. One of the most prevalent uses in practice today is to provide access to part catalogs for end users.

CONCLUSIONS

The complexity of modern enterprises creates numerous challenges for software applications. These complexities are a direct result of enterprise structure, activities, and data. As complexity increases, the cost of systems to support the associated applications rises dramatically. While numerous vendors cite the benefits of implementing large-scale systems, the case for such applications has not been clearly made in terms of costs and benefits. It remains to be seen if such systems will provide added value to the end users.

What is clear is that databases supporting each of the domains must be provided along with applications that support activities within domains. The PDM, MES, and ERP systems are current examples of attempts to address the needs in this area. The scope and usage of these systems are evolving as vendors try to address user needs. By using such systems, enterprises need to be aware that they are establishing future legacy systems. Strategies must be developed to transition from previous legacy systems.

Given the variety of applications (and their sources), the need for integration or sharing of functionality is apparent. Future solutions will require the successful integration of multiple applications. Compatibility with the Internet is a must for applications that use and display information.

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BIOGRAPHY

John Jackman is an associate professor in the Department of Industrial and Manufacturing Systems Engineering at Iowa State University. He received his Ph.D. in industrial engineering from The Pennsylvania State University. His research interests are in the product realization process, engineering metrology, and simulation. He has worked in the pharmaceutical, aerospace, electronics, and simulation software industries.

CHAPTER 12.4

INTERFACING TECHNICAL IE SYSTEMS WITH BUSINESS SYSTEMS

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This chapter will discuss the interface of technical data developed by industrial engineers with company business systems. It covers the industrial engineer's use of data developed and maintained within available business systems, as well as the use of data developed and maintained by industrial engineers. Systems' interfacing is not limited to industrial engineering data and applications. Interfacing all sorts of technical data with other systems will provide a company with many of the benefits that will be discussed. Not to be confused with system integration, this chapter deals only with systems interfacing, the sharing of data between distinct systems. The chapter is intended to be a guide—not an instruction manual—to encourage thought as to how system interfacing can benefit an organization.

TYPES OF INTERFACES

System interfacing is the sharing of data between two or more distinct computer systems or applications. A system interface is the tool (software applications and hardware) to accomplish this task. The system interface may access or develop data on the same personal computer, mini computer, or mainframe across a network or the Internet. The interface may use source data developed and maintained by other systems to aid in the development and maintenance of new data. It may develop or maintain data for other company applications to use. It could do both in a single application, or it may use only information developed and maintained by other systems for reporting purposes.

There are several types of interfaces that should be considered, as they each have their own benefits and drawbacks, when making a decision on the type of interface to be applied. Following are some common types of interfaces used in industrial engineering (IE):

- Industrial engineering application to business system
- Industrial engineering application to file to business system
- Business system to industrial engineering application
- Business system to file to industrial engineering application

These interfaces may be combined in such a way that data can be supplied by one system, processed by another, and returned to the original system or a third system. Figure 12.4.1 shows multiple interfaces of an IE application and data with multiple company system applications.

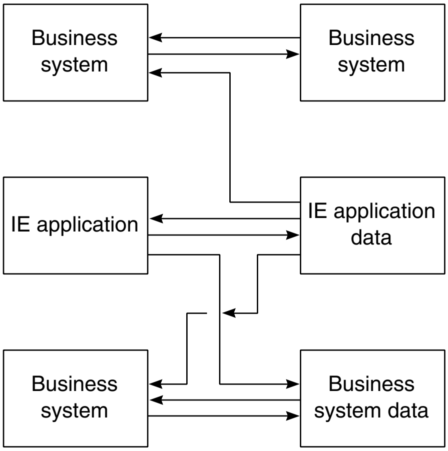

FIGURE 12.4.1 Interface of IE application/data with multiple business systems.

Industrial Engineering Application to Business System

In this case an industrial engineering application would develop and maintain data directly into the database used by a business system (see Fig. 12.4.2). Consider, for example, an industrial engineering application that develops part routings. As the routings are developed, data is saved to a capacity planning system. This may be beneficial if the business system and industrial engineering application are both on the same hardware platform. Otherwise, if the hardware responsible for the business system is not available, the industrial engineering application may not be able to perform its necessary functions.

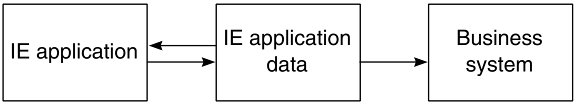

FIGURE 12.4.2 Interface of IE application to business system.

Industrial Engineering Application to File to Business System

An industrial engineering application could also develop and maintain data into a data structure, or file, located on its hardware platform. The industrial engineer would then be required to copy this data to the location that would be accessed by the business system. The business system would then access this file. In the previous example, the part routing information would be written to a file. The planner would then copy the data to the location required by the capacity planning system. Once successfully copied, the capacity planning system could then use the data. This may be beneficial if the business system and industrial engineering applications are on separate hardware platforms. By using an intermediate or transfer file, both the business system and industrial engineering application could run independent of the other's hardware platform, as depicted in Fig. 12.4.3. However, the planner must remember, or have some automated mechanism, to copy the data from the part routing application file to the location required by the capacity planning system, and both hardware platforms must be available at that time.

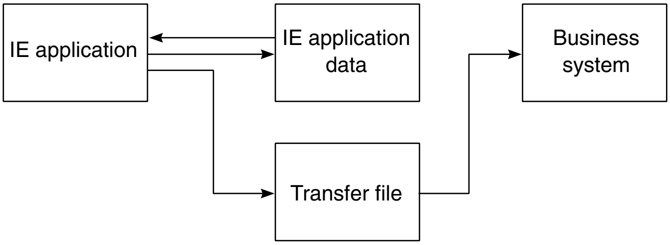

FIGURE 12.4.3 Interface of IE application to file to business system.

Business System to Industrial Engineering Application

In this application, a business system would develop, maintain, and save data directly into the database used by the industrial engineering application (see Fig. 12.4.4). An example of this would be an accounting system that could calculate overhead percentages. As the percentages are calculated, they are written to the database used by an industrial engineering application that calculates total cost for a product. This type of interface may be beneficial if the business system and industrial engineering application are both on the same hardware platform. Otherwise, if the hardware responsible for the industrial engineering application is not available, the business system may not be able to perform its necessary functions.

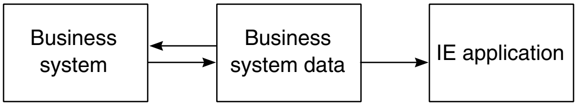

FIGURE 12.4.4 Interface business system to IE application.

Business System to File to Industrial Engineering Application

In this final application a business system would develop and maintain data into a data structure, or file, located on its hardware platform. The industrial engineer would then copy this data to the location that would be accessed by the industrial engineering application, which would then access the data. For the preceding example, the overhead percentages would be written to a file. The industrial engineer would then copy the data to the location required by the application. Once successfully copied, the application could then calculate cost with the overhead percentages. This type of interface would be beneficial if the business system and industrial engineering application are on separate hardware platforms. By using an intermediate or transfer file, both the business system and industrial engineering application could run independently of the other's hardware platform (see Fig. 12.4.5). However, the industrial engineer must remember, or have some automated mechanism, to copy the data from the business application file to the location required by the industrial engineering application. Both hardware platforms must be available at that time.

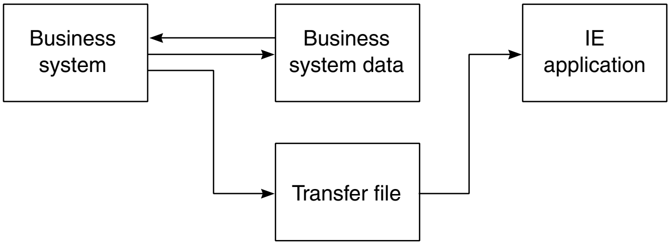

FIGURE 12.4.5 Interface business system to file to IE application.

There are techniques that can be used to minimize the impact of one of the hardware platforms not being available. One technique is to periodically copy the intermediate file from one platform to the other. Depending on the applications, there may be problems knowing what data has been processed and what data has not. The preferred approach is to design intermediate interfaces that run in the background and are invisible to the users. The interfaces would automatically check for updated information and copy it from one application to the other. This would enable both the business systems and industrial engineering applications to run independent of each other, and possibly eliminate the use of intermediate or transfer files. Intermediate files may remain a required entity if they are needed to determine what data has been processed and what data has not.

DESIGNING THE SYSTEM INTERFACE

When designing the interface, consider functionality, the resources available, how much time before it is required, the data that can be used from other systems, the data being developed, and any applications that will be accessing the data.

There are many uses for accurate industrial engineering data and many of those will be explained later in this chapter. Available external data, where the industrial engineering data can be used, and the logic necessary to perform the required functionality are the primary considerations in the design process. A complicated system may require brainstorming sessions, where all ideas are noted. The ideas are then discussed and pared down into a prioritized wish list. The list can then be used as a reference of the required functionality for the interface design.

Designing a system interface is a team effort because it will be necessary to deal with representatives from other functional areas. Depending on the required functionality, it may be necessary to work with information systems, accounting, planning, and/or production groups. It is very important to include these areas very early as part of the project steering committee. It is important to gain the trust of other functional departments when either supplying them with data, or using their data for development of industrial engineering data. By including others early on in the project, they will take ownership in the efforts by being part of the team, and will be more inclined to offer data, suggestions, resources, or other information—which may be needed.

For the system resources, consider both the hardware and software development. Both must have the technical capacity for the additional work being required of them. It is important not to let the software application developer design the system. Whether in-house staff or third-party developers are being used, it is important that functionality issues be addressed. The technology issues should not overshadow functionality ones. You need a mousetrap that works, not necessarily the best mousetrap. The technology should be sound, but with the changing environment, the life expectancy of current technology is relatively short. Technology extras for the sake of technology, and not functionality, may delay implementation and do more to hinder functionality than help. A good rule to follow is to keep it as simple as possible.

It is important to consider how soon the interface is required because that may determine the extent of the functionality. It may be necessary to limit the functionality in order to have a functioning system by a certain date, or to implement in stages, and get the functionality in pieces, while enabling limited functionality sooner. A good program specification with realistic time estimates for each functional module is a useful tool in making this determination.

During the brainstorming and design process, it is important to consider the final goal. Ask questions such as

- What data will we be providing and to whom?
- Do we have the proper source data to provide that data?
- Is the quality of all source data acceptable?
- Who will be providing that data and in what format?
- What is the hardware configuration?
- Will we interface with one or several applications?

The interface may be a stand-alone application with the sole purpose of transferring data between applications, or it may be designed within a larger software application. Either way the system interface should be designed and programmed for the specific need. The system interface may consist of specifically coded software applications or programs, which may be purchased from third-party suppliers or developed in-house. The system interface may be a combination of both. For instance, there are knowledge-based expert systems that can be purchased. The industrial engineers or "knowledge experts" do the programming, much like putting together a flowchart or decision tree. The inference engine of the expert system then reads the flowchart to build a customized application that can both perform the industrial engineering functional requirements and handle the system interface.

The downside of coded applications is that as changes occur, software developers may be needed to make changes to the system. The resources to make the changes may not be available when they are needed, and can be expensive and untimely.

A knowledge-based expert system can much easier be adapted to the changing business environment. It is typically maintained by the industrial engineering staff rather than by software developers. This enables changes to be made internally, when they are needed, rather than relying on others to make them. With today's popularity of personal computers, networking applications, and relational database management systems (DBMS) there are tools available for developing either coded or knowledge-based expert systems that would perform the necessary system interface.

DATA MAINTAINED BY INDUSTRIAL ENGINEERS

One key function in industrial engineering is to evaluate the results of improvement in productivity. An important step in this process is interfacing technical systems with business systems, thus reducing duplication of efforts and improving the quality and consistency of information. Industrial engineers are responsible for making products and services faster and better, at a lower cost and safely. To accomplish this, industrial engineers must be knowledgeable in manufacturing, process optimization, customer service, quality, analysis and problem solving, cost estimating, and inventory strategies. But industrial engineers must also develop, maintain, and analyze data. The following list is representative of data industrial engineers are responsible for developing and maintaining.

- Process lead times
- Operation time standards
- Work instructions
- Operating procedures and practices

- Work measurement
- Operation methods
- Multiactivity analysis
- Process routings
- Part specification data
- Subassembly/assembly data
- Bills of material (BOM)
- Line balancing
- Material handling
- Production labor cost
- Cost justifications
- Productivity statistics
- Tools and fixtures
- Product cost estimating
- Facilities and layout
- Ergonomic analysis

Much of this data can be developed for one area of need and used to assist in other areas. Take, for example, industrial engineers' responsibility for determining and documenting the best method. To accomplish this, industrial engineers must analyze and measure the work. The work measurement may be a time study or measured based on a predetermined motion time system such as MOST or methods time measurement (MTM). Once the basic elements are measured and validated, they can be put together and used to set standards at a higher level, such as operations. These standards may be used in process routings, work instructions, or to determine a balance of the production line.

RECEIVING DATA FROM OTHER SYSTEMS

To improve industrial engineering productivity, it is beneficial to obtain data from other systems, as this reduces the amount of data the industrial engineer needs to develop and maintain. In determining what data the industrial engineer can use, it becomes necessary to think beyond the typical scope of industrial engineering and to look at the big picture. Asking some general questions initiates that thinking.

- What problems are to be addressed?
- How many parts or part families are there?
- What machine groups are being considered?
- What tooling and fixtures are required?
- How do we handle engineering changes?
- What are the processes?
- What data would be beneficial?
- Who would have that data?
- What other data do they have?

To answer these questions, the industrial engineers have their observations, experience, and knowledge to draw from. Information in the form of data is available from many sources.

- Orders/order entry
- Engineering change notices
- Forecast system
- Machine assignments
- CNC programs
- Tooling
- Fixtures
- Part specifications
- Part lists (BOM)
- Vendor part catalogs
- MRPII or enterprise resource planning (ERP) system
- CAPP system
- Process detail sheets
- Production planning system

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- Safety information
- Bar code systems
- Quality management system
- CAD drawings
- Routing system
- Warehouse management system
- Maintenance management system
- Payroll system

The data may be contained within another system's database or it may reside in an external file. The database may be an American National Standards Institute (ANSI) standard DBMS or a customized proprietary database. Oracle™ and Microsoft Access™ are examples of a DBMS. An external file may be a spreadsheet or an ASCII text file.

Interfacing to the source data reduces, if not eliminates, duplicity of that data, thus reducing the amount of data that the industrial engineer must manually input and maintain. As a result of minimizing the amount of data to maintain, addressing changes as they occur becomes easier and quicker, saving industrial engineers time.

As an example, suppose there is a need to determine the standard time for 100 parts in a particular operation. All parts require one of three load and unload methods, and a process time determined by the part volume and material. Assume that the part information, including dimensions and material, resides in a part specification system, stored in an ANSI standard DBMS (see Fig. 12.4.6). From experience with the operations and a quick look at the drawings, the load and unload method used for each part can be determined.

Part number	Material	Length	Width	Height
A12345	10	1.000	0.013	0.250
B12345	11	0.750	0.025	0.250
C12345	12	1.250	0.019	0.125

FIGURE 12.4.6 Sample parts specification data.

One method of determining the standard time would be to use a calculator to calculate the process time and add the load and unload time for each part. If this had to be done only once, the previous example may be a viable solution. However, it is typical for things to change. There are method changes, tool changes, equipment changes, part design changes, and parts added to and deleted from production.

Another method of determining the standard time would be to create a spreadsheet, ASCII file, or table that included the load and unload method assignments, and another containing the times for those methods (see Figs. 12.4.7 and 12.4.8). The load and unload methods and times would be determined by the type of fixtures used for each part. A system interface, either internal or external to an industrial engineering application, could be designed to

Part number	Load and unload method
A12345	2
B12345	1
C12345	3
CK3445	3
K43345	1
MU9843	3
XI83K2	2

FIGURE 12.4.7 Method identification for loading and unloading parts.

Load and unload method	Minutes
1	0.2
2	0.4
3	0.6

FIGURE 12.4.8 Sample times for loading and unloading methods.

- Sequentially read through the part specification database to get part material and dimensions. This would ensure that all parts are being processed.
- Read the load and unload method assignment based on the part number being processed from the data shown in Fig. 12.4.7.
- Read the load and unload method time based on the part number being processed from the data shown in Fig. 12.4.8. If information is missing for a particular part or method, a message could be displayed that would identify the missing information. The information could then be added to the appropriate tables, and the parts reprocessed.
- For this example, the process time is calculated based on part volume and material. The industrial engineering application would calculate the volume and process time for the operation. Different calculations could be used for different types of material.
- Add the appropriate load and unload time.
- Store the part number and standard time for reference.

As changes occur, the source data in Figs. 12.4.7 and 12.4.8 can quickly and easily be maintained. In Fig. 12.4.8, for example, a method improvement that reduces the time for load and unload method 2 from 0.04 min to 0.03 min would require changing the 0.04 to a 0.03. Similarly, in Fig. 12.4.7, a change in the load and unload method for part C12345 to method 2 would require a change from a 3 to a 2. Changes to part specification data would be maintained by the part specification system—a business system. Subsequent processing by the industrial engineering application, with an interface to the part specification data, would automatically incorporate changes into new standard times for affected parts.

The application could also easily be expanded to calculate standard times for the entire part routing based on the information in external files. A table that contains part routing information (Fig. 12.4.9) can be added to the industrial engineering application. By including machine assignment to the load and unload table (Fig. 12.4.10), the application will have the

Part number	Operation number	Machine center
A12345	10	SAW
A12345	20	CNC1
A12345	30	DP12
A12345	40	RMR1
B12345	10	SAW
B12345	20	CNC4
B12345	30	RMR3
C12345	10	SAW
C12345	20	CNC3
C12345	30	CNC4
C12345	40	DP03
C12345	50	SAND
C12345	60	RMR1
C12345	70	CLEAN

FIGURE 12.4.9 Sample part routing file.

Part number	Machine center	Load and unload method
A12345	SAW	1
A12345	CNC1	1
A12345	DP12	1
A12345	RMR1	1
B12345	SAW	1
B12345	CNC4	2
B12345	RMR3	1
C12345	SAW	1
C12345	CNC3	3
C12345	CNC4	3
C12345	DP03	2
C12345	SAND	1
C12345	RMR1	1
C12345	CLEAN	1

FIGURE 12.4.10 Sample file of method identification for part loading and unloading.

information it needs to calculate standard times for all operations in the part routing. Any changes to part routings can then be done external to the industrial engineering application, and programming changes will not be required. And again, subsequent processing by the industrial engineering application, interfaced to the source data, would automatically incorporate changes into new standard times for affected parts.

WHERE THE DEVELOPED DATA CAN BE USED

System interfacing should not be restricted to the development of data. It is also beneficial to interface data developed in industrial engineering with other business systems. Data that the industrial engineer is responsible for has many uses to the company. By interfacing with these business systems, it is assured that data is consistent and accurate. Systems that would benefit from consistent and accurate industrial engineering data include

- Incentive plans
- Staff modeling
- Staffing by craft and skill level
- Labor planning
- Cost modeling
- Cost estimating
- Cost analysis/control
- Cost accounting
- Production scheduling
- MRPII/ERP
- Work orders
- Performance management
- Capacity planning
- Payroll
- Business planning
- Ergonomic analysis
- Quality management
- Warehouse management
- Maintenance management
- Layout simulation
- Budgeting
- Kanban simulation
- Inventory management
- Process/production simulation
- Synchronous flow manufacturing
- ISO 9000

Let us expand on the example from the data sources section. Suppose the labor-hours are needed for all parts so that any part mix can be scheduled and the inventory buffer quantities

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and the earned hours for an incentive system can be calculated. Also, suppose that those 100 parts required an average of five operations to be manufactured. This scenario would need 500 operation steps to be measured and documented, and 100 part routings reviewed. Additionally, there would be 1100 data elements manually updated in the business systems: 500 for the kanban simulation system, 500 for the scheduling system, and 100 for the incentive and/or payroll system.

By interfacing with these systems, accurate information is shared quickly and consistently. Fig. 12.4.11 shows the source data (the boxes in the column on the left), the interface (the lines and arrows), the industrial engineering application, and the business systems (the boxes in the column on the right) being supplied information from the application. The standard times calculated by the industrial engineering application would automatically be fed into the business systems, eliminating the clerical task of data entry and the possibility of manual errors.

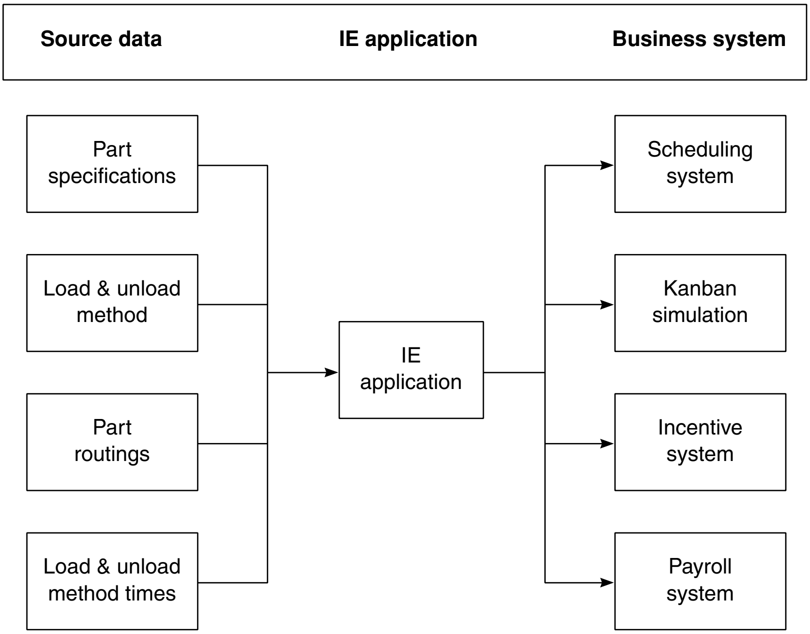

FIGURE 12.4.11 Interface of source data to IE application, with interface of IE application to business system.

Standard times can be determined without studying every part on the floor. Once representative parts have been measured and validated, work measurement can be accomplished for nearly all parts based on part specifications and drawings. This will result in complete and accurate data (direct cost) with limited effort. When combined with indirect cost and long-range forecast, direct cost can be used in calculating overhead percentages.

BENEFITS OF ACCURATE INDUSTRIAL ENGINEERING DATA

Interfacing with source data will not only reduce the time necessary to develop and maintain data, it will also increase the accuracy and consistency of the data. An increase in the quality of data is important because it will increase the quality of the applications. Thanks to interfacing between systems, the following benefits of quality data can be achieved:

> *Systems using the same data will get consistent results.* If design engineering says the part weighs 2 lb, then shipping, industrial engineering, and ergonomic studies will use the same weight.
>
> *Data is there when it is needed, immediately.* There is no wasted time looking for data or waiting for someone to return from vacation. Data will not disappear when someone leaves the company.

Examples of the benefits are discussed in the subsequent section. The benefits can be divided into two general categories: benefits to the company and benefits to the industrial engineer.

BENEFITS TO THE COMPANY

Proper utilization of system interfaces will quickly share information developed by industrial engineers with other systems. By making the consistent and accurate data widely available, company management has the information they need to make better and more timely decisions.

Simulation models are one of the powerful tools for industrial engineers. They provide management with information necessary to make accurate labor assignments, productivity improvements, cost estimating, production scheduling, forecasting, and so on. The accurate data provides the consistent and reliable results in the area of production planning, plant layout, and scheduling, to name a few.

Throughput time can be reduced through productivity improvements, proper line balancing (staffing), scheduling, and materials forecasting. This will enable a company to increase production at current staffing levels. Or staffing and material inventory can be reduced to only those levels necessary for production. This will also result in an improvement of cash flow by reducing working capital. Proper scheduling and line balancing will also result in an improvement of machine utilization.

For example, the production schedule provides the list of products and quantity required based on orders. Industrial engineers provide the time standard to manufacture these parts at the appropriate work centers. Through the interface, the number of people required in each department can be accurately determined. This way the production control will release the orders based on the available labor and equipment capacity.

Fast and accurate cost estimating is also possible. Quick and accurate proposals in the bidding process will increase the opportunities for additional orders. This will result in either more profitable orders or potentially receiving more orders by eliminating estimates that are inflated due to the unknown labor content. For example, suppose that a cost-estimating application is interfaced with data from the business systems responsible for materials, tooling, labor, and overhead. It is possible to quickly estimate cost as a by-product of the design of the product. By comparing any design changes to an initial design, the engineer can quickly see the impact of such changes on the cost of the product.

Cost justification for the purchase of new equipment or tools and make/buy decisions can be made knowing that information used in these decisions is reliable. The method to produce a part using a proposed tool, equipment, or machine can be defined in a predetermined fashion. If the savings can pay off the cost for the new equipment or tools in an acceptable period of time (whatever is appropriate for your situation), then the investment is justified. This methodology shows that without actually investing any money and using the techniques available, an industrial engineer is able to provide a cost-benefit analysis.

Workers' compensation payments are a problem with many companies. Two contributing factors to injuries occurring in the workplace are employees not trained to follow proper procedures and ergonomic risks inherent to an operation. Ergonomics deals with the safety aspects of the operations. The analysis of the ergonomic risks involve the analysis of the ergonomic data (force, posture, repetition, etc.) associated with the method. By interfacing the method and standard time to the ergonomic study, the industrial engineer is able to develop and analyze the ergonomic attributes. Modifying the method to reduce the ergonomic risks will provide a safer, more efficient method that can be used to properly train employees.

BENEFITS TO THE INDUSTRIAL ENGINEER

The primary benefit to the industrial engineer is that a properly designed interface provides a fast, easy way to use accurate and consistent data—although there is a necessary investment of time to construct and implement a proper system interface. But since data input in the development of data and sharing that data with other business systems is reduced, the day-to-day operations of keeping data up to date and current will require much less time. This will give the industrial engineers more time to handle other important tasks.

A system interface will reduce the duplicity of data and minimize the effort required for data maintenance. If maintenance is quick and easy, there is a better chance that as changes occur, the changes will be reflected in the data that is affected. It will not be a task that industrial engineers do not have the time to address, since they can quickly make the necessary changes. If changes are not made in a timely manner, the data does not reflect the situation on the shop floor. When this occurs, the integrity of the data can become suspect. Data that accurately mirrors the current situation on the shop floor is easily accepted and less likely to result in challenges from the workers. Consistently accurate data builds a level of trust between management and the employees.

With a system interface, much of the guesswork is removed and the result is consistent and accurate data. Related information, such as tools, materials, and craft requirements can be linked to the method electronically in an interface. In this way, information related to the method can consistently be documented with the method information.

With an industrial engineering application that interfaces with organized and accurate data, it is possible to quickly and accurately develop and maintain data without the benefit of actual observations. Again, using work measurement as an example, it is possible to quickly have substantial coverage of parts, before observing the production operations on the floor. This can be accomplished by applying what is known of the process for each part. Take, for example, the information in Figs. 12.4.6 to 12.4.8. Assume that the standard time for part number D12345 is needed, and the drawing describes the material and dimensions. Also assume that the load and unload method to be used can be determined by the shape of the part, also visible on the drawing. By entering that information in the appropriate tables and processing that information, the standard time would be calculated automatically without always observing the part in production. The same process can apply for other operations necessary to produce the part. It is recommended that when the part is on the floor for production, industrial engineers validate the process, thus validating the calculated standard times.

CASE STUDY

The following situation recently occurred in a retail environment. Operation time standards were manually entered into a staffing system. Staff scheduling was required for over 100,000 employees. Time studies were used to measure a majority of the hundreds of operation tasks. However, no performance ratings were performed on the store associates being studied. This is contrary to standard industrial engineering practices, and brings into question the validity

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of the standards. A direct measurement approach was used to develop engineered time standards for a limited number of operation tasks. Additionally, the work measurement data was not shared between the different divisions within the company. Repetitive effort by a different team was required to develop standards for each division.

This approach requires an extensive effort to

- Develop and maintain operation standards.
- Maintain and update the staffing system.
- Develop operation standards based on varying conditional drivers (season, division, store type, store size, sales, and traffic).
- Develop cross-divisional operation standards.

To resolve these problems, all manual methods, except for customer engagement, were analyzed using a predetermined motion time system (PMTS) such as MOST. Standard data and engineered standards were developed for these tasks so that a consistent database of tasks could be used across all store types.

Time study and regression analysis of the customer engagement portion of the task continues to be used. These findings are added to the measurable portion of the operation standard as a wait time.

The various conditional drivers (season, division, store type, store size, sales, traffic, etc.) were developed and are maintained in a database. The AutoMOST expert system is interfaced with the driver data to create standards based on the different sets of conditions that enables accurate standards for any of the conditional driver situations to be established quickly. Interfacing AutoMOST with the staffing system eliminated the need for manual input of standard times into the staffing system. As a result, tasks and task times are automatically and accurately updated, which enables the stores to accurately meet staffing needs based on their varying forecasts.

By using the standard data approach, many benefits have been achieved:

- It is easier and quicker to develop and maintain operation standards.
- A greatly reduced effort is needed to develop standards based on the varying conditional drivers (season, division, store type, store size, sales, and traffic).
- The ability to develop cross-divisional operation standards.
- The ability to easily develop standards for all operation tasks, including those containing customer engagement.
- Enable the application of AutoMOST in the standard setting process.

Using AutoMOST has the following benefits:

- After an initial development effort, operation standards are automatically set in minutes.
- Operation standards are automatically set for any mix of condition drivers (season, division, store type, store size, sales, and traffic).
- Developed standards are consistent and accurate.
- Staff scheduling data is more consistent and accurate.

SUMMARY

System interface is the sharing of data between distinct computer applications. The interface may be from business systems to industrial engineering applications, from industrial engineering applications to business systems, or a combination of both, and more than a single industrial engineering application or business system may be involved. It is important not to sacrifice the desired functionality of the application when designing an interface. Functionality, resources, and timing are the critical concerns.

Industrial engineering data supports many facets of a company. In accounting, human resources, production, planning, inventory, layout design, logistics, quality, and more, industrial engineering data is there. The accuracy and consistency of this data can play a large role in the success of a company. Interfacing an industrial engineering application with business systems can quickly support these areas with quality data. For these reasons, interfacing industrial engineering applications with business systems can greatly benefit both the industrial engineer and the company.

GLOSSARY

Knowledge-Based Expert System A subset of the artificial intelligence technology that is used for decision making by enabling users to have the problem-solving skills of multiple experts.

Systems Integration To incorporate a small system into a larger system.

Systems Interface The sharing of data between two distinct systems.

BIOGRAPHY

Albert F. Lucci is a senior technical consultant at H. B. Maynard and Company, Inc. He received his Bachelor of Science degrees magna cum laude in mathematics and computer science from Point Park College in Pittsburgh, Pennsylvania. He has over 20 years of experience in designing, developing, and applying industrial engineering software products. He has designed system interfaces for many types of industries, including plastic manufacturing, electrical connector manufacturing, tire manufacturing, powder metal manufacturing, medium-duty truck assembly, and retail.

CHAPTER 12.5

ARTIFICIAL INTELLIGENCE AND KNOWLEDGE MANAGEMENT SYSTEMS

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Artificial intelligence (AI) and knowledge management systems (also known as expert systems) have been used successfully in many applications of interest to the industrial engineering (IE) community. This chapter will discuss the history and background of AI and how it has evolved into a modern practical technology of wide use to the IE and manufacturing sectors. Several case studies are briefly presented for the purpose of illustrating how expert systems are useful in the following types of areas: (1) methods engineering/work measurement, (2) industrial energy efficiency, (3) pollution reduction, and (4) expert systems in manufacturing. The promise and potential of neural networks is also briefly discussed.

THE BASIC THEORY AND HISTORY OF ARTIFICIAL INTELLIGENCE

General Philosophy of AI

As humans we have introspectively questioned how our minds work at least since the time of ancient Greece. How our minds reason is a topic that intrigues many of us. In modern times, the answer to this question has been pursued from many different perspectives. From the medical perspective, we call it neurosurgery, neuroanatomy, neurology, and psychiatry. From the clinical counseling perspective we have psychology, learning theory, and the behavioral sciences. From the perspective of mathematics we have the studies of logic, theory of computation, and theories of reasoning. From the linguistics fields, we have computational linguistics. From mechanical engineering, we have robotics. And from electrical engineering, we have computer vision. Each discipline attempts to understand the working of the human mind from its own perspective, relying of the tools and traditional models with which it has become familiar.

Modern artificial intelligence (AI) attempts to integrate the insights and experimental techniques from all of these fields into a cohesive model that can be implemented as algorithms on a computer. The scientific idea behind this approach is that we cannot really arrive at anything more than speculative conjectures about how the mind functions until we can precisely model and reproduce its behavior on a computational device, such as a computer, that has fully specified and accounted for all the various functions and abnormalities of the human mind. When we can do that, then we can claim we know how the mind works. Until that time, we are left with a mixed bag of various approximations that often conflict with each other because of their limitations.

AI attempts to come to a provable understanding of the human mind: proven when we can understand it so completely that we can artificially (as opposed to naturally) reproduce it. This is the final scientific goal and driving motivation behind AI.

Since we are probably still many years away from realizing this goal, we are left for the moment with these various limited, and sometimes provably incorrect, approximations. Not to despair. Some of these approximations have turned out to be close enough to be quite useful in practical ways. Many of the readers of this handbook will already have heard of many of these approximations. They are referred to as expert systems, neural networks, object-oriented programming, cortical thought theory, genetic algorithms, various search and pruning strategies, and so on. These and others are the direct results of various models of human reasoning, most of which originated in the AI labs of primarily four universities: Massachusetts Institute of Technology (MIT), Stanford University, Carnegie Mellon University, and the University of Edinburgh (Scotland).

The Early History

The Greeks laid the mathematical foundations of modern AI with their theories of reason and logic. It required the advent of the modern electronic era and the digital computer to go much beyond ancient theory and the significant limitations (too slow) of "working it out on paper." But to give the Greeks proper credit, we start with modus ponens. Modus ponens is still considered the foundational cornerstone of modern deductive logic. Simply stated, it says that if you have a rule such as A → B (read: A implies B, or alternately, if A then B), and if you then discover that you do indeed have a situation where you know A is true, then modus ponens tells you to conclude that B is also true. Fairly simple so far—and not apparently too useful except to impress your friends with how firm a grasp you have of the obvious.

By using modus ponens, you can "chain" these rules together, for example, if you have a whole bag full of rules (in the late twentieth century that bag full of rules was called a *rule-base* or *knowledge-base*). Among the many different rules in the bag were the following four: B → C, and D → E, and A → B, and C → D. Now if someone comes along and tells you that A is true, modus ponens allows you to conclude that E is also true. This is not quite so obvious and begins to reflect intelligent reasoning if only we could match those rules up a little faster than doing so by stone tablet and chisel (or even with paper and pencil).

When we implement this idea on a computer, we achieve a basic rule-based expert system. A more concrete example might be useful in illustrating this concept.

ABC corporation's plant number 1 has decided to experiment with expert systems. They purchase one and ask all the departments to start entering into the rule-base their observations about how things work in the plant. The following four rules were just some of the rules entered by first-shift personnel:

1. Mildred in the human resources (HR) department notices that every time the cooling fans are turned on, they move so much air that it tends to blow loose papers into disarray. So Mildred adds a rule to the rule-base that says, "*If the cooling fans are going to be turned on, then notify HR to put loose papers away.*"
2. In the packing department, Joe notices that the widgets are sticking together in the packing crates and after a thorough quality analysis has been performed, it is determined that this is because there is too much moisture in the widgets. So the packing department enters a rule into the rule-base of the expert system that says, "*If the widgets are sticking together, then the widgets are coming off the assembly line with too high a moisture content.*" (Let A

represent "widgets sticking together," let B represent "too much moisture content"; this is equivalent to our first rule: A → B.)

3. The industrial engineers now begin to investigate the process to determine why the widgets have too high a moisture content. They discover that the water temperature in the process vat is too high and that it needs to stay under 150°. (Letting C represent "water in process vat is more than 150°," we now have the equivalent of the rule: B → C.)
4. Harriet from engineering has already entered a rule that says, "When the vat temperature is above 150°, you should turn on the cooling fans." (Letting D represent "turn on the cooling fans," we now have the rule: if C then D.)

With all of this information now entered into the expert system's rule-base, presumably along with many other independent observations/rules from others in other departments, the shift changes. About halfway through the second shift, Harry, a worker in the packing department, notices that the widgets are sticking together. He enters this information into the expert system just to see how helpful this thing can be. As soon as he does, the expert system outputs the following recommendations: (1) tell HR to put away loose papers, and (2) turn on the cooling fans.

No single person may have ever before linked sticky widgets in packing with the need to tell HR to put away loose papers, but the expert system, using an inference engine capable of chaining rules through the successive use of modus ponens has now formalized that relationship. Many would agree that these results are at least similar to intelligent reasoning, albeit artificially produced.

The First Half of the Twentieth Century

But we're getting ahead of ourselves—rule-based expert systems were not invented until the early 1970s. We still need to find out about some of the more theoretical groundwork that was laid prior to that because it has far reaching effects on the potential and direction of AI, not only its practical uses today, but also its future.

Alan Turing was the foremost modern mathematician to theorize a thinking machine. In the 1930s, he developed the theory for what we now call a *Turing machine*. The Turing machine is a hypothetical machine with an infinite memory and an infinite amount of time to perform calculations. Turing proved it was capable of "reasoning" to *any* rational conclusion by first constructing a state space of all possibilities and then searching that state space until a solution was found. This is the premier foundational theory that undergirds all of AI, not to mention all of computer science. Included within its boundaries is the theoretical basis that describes all that may someday be done in AI, and all that may never be done.

John von Neumann attempted to build a Turing machine with the limitation that it had a large memory (not infinite) and a limited amount of time to perform the construction and search of the solution's state space. With these limitations, such a machine could not solve *any* rational problem, but it could still solve a large number of practical problems, and therefore was a promising enterprise. The von Neumann machine is the archetype of the modern electronic digital computer. It was first used for calculating missile trajectories in the 1940s.

The Second Half of the Twentieth Century

By the time the wars of the 1940s and early 1950s were over and the universities in America started getting back to business as usual in the latter 1950s, there reemerged an academic interest in building a machine that could reason. In 1956, the first ever national conference on artificial intelligence was held at Dartmouth College. This conference spawned the term *artificial intelligence*. In those early years of AI, initial projections of the progress that AI would make by the turn of the century were greatly overstated. However, as is typically the case with a new science or major technology, the reality falls short of the near-term projections and exceeds the long-term projections. We're still waiting to exceed the long-term projections, but many impressive advances have already been made.

In the first 15 years of AI, most of the impressive successes of AI came from MIT. At first there was the obvious work to be done of exploiting Turing's theorem. During this phase of AI, many theories and techniques were developed for constructing and searching state spaces for various types of problems. Although this work resulted in many early successes, it proved to be inadequate to describe what was actually going on in the human mind, and the focus turned to finding more humanlike cognitive models of reasoning. This is not to say that these search techniques were ineffective or completely abandoned. It was primarily these search techniques, combined with the heuristic knowledge modeling of rule-based expert systems, that produced the astounding success of IBM's Deep Blue in May of 1997 by defeating the World Champion Grandmaster, Garry Kasparov, in a six-game chess match.

Another early impressive success was the demonstration of the ability to create an artificially intelligent Rogerian psychologist—that is, a computer program that could expertly carry on counseling therapy sessions with troubled humans. This system, called *Eliza,* was one of many contributions to AI from MIT in the 1960s. Eliza was impressive in at least two notable ways. First, transcripts of sessions between Eliza and real patients were not detectable by many practicing Rogerian psychologists as being anything other than genuine sessions between a real patient and a competent psychologist. This was a very impressive outcome. The second, and perhaps even more startling, discovery was the simplicity of the algorithm and knowledge-base necessary to accomplish this feat. A competent Rogerian psychologist studies for years to achieve the required level of competence. A computer program could be written to replicate that capability in a matter of days (once you knew how to approach the problem)! This realization that human intelligence could be simulated with very simple means was only one of many such disturbing discoveries that would come from AI labs. The perceived complexity of the human intellect was beginning to be understood as something more mundane than originally thought.

The Advent of Expert Systems

One of the most practical developments to come from AI labs was the rule-based expert system. Two major concepts formed the basis for modern expert systems. The first was the realization that knowledge was better represented in human languagelike symbols. For example, a symbolic representation of knowledge might be in the form of words in an if-then statement: "If the pressure goes above 250 mm mercury and the temperature is above 190° then the relief valve should be opened." This notion of symbolically representing knowledge is common today, but at the time in the late 1960s, it was a significant improvement over the traditional approach of using six-letter variables and program pointers to represent everything in the form of data (as opposed to grammatically correct English statements of knowledge).

The second major concept, which we introduced in an earlier example, was the development of an *inference engine.* An inference engine is a computer program that can methodically apply modus ponens to a potentially large and unordered collection of if-then statements (called *rules*), with the result that the program (inference engine) could now "reason" to the solution of real-world problems. This was thought to be reminiscent of the problem-solving abilities of human experts—hence the term *expert system.* Using the combination of an inference engine and rule-bases full of symbolic knowledge, the concept of *symbolic processing* (or symbolic reasoning) was born. This concept was to be, and still is, one of the fundamental principles of AI.

The first expert systems resulted in some impressive successes. An example is the MYCIN work from Stanford University. This was a medical diagnosis system capable of more expertly diagnosing certain classes of blood disease than some human doctors specializing in the field [1].

Another impressive expert system success from the Stanford Research Institute was PROSPECTOR [2]. This expert system operated by allowing a geologist to describe the geological observations primarily on the surface of the ground; PROSPECTOR would then

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begin to ask questions of the user about the presence of other geologic and terrain information, resulting in a prediction of the likelihood of various underground mineral deposits. Reportedly, one of the first uses of PROSPECTOR resulted in the successful prediction of the existence of a large molybdenum deposit that was sufficiently profitable to pay for the entire expert system development effort.

Digital Equipment Corporation (DEC) developed a commercially successful (and very large) expert system to configure VAX computers. This system was originally called *R1* and then was later renamed *XCON* [3]. One DEC insider reported that this system was so critical to rapidly determining the proper configurations of VAX computers to keep up with the pace of orders that without it DEC could not be profitable—an impressive strategic success.

These three examples, MYCIN, PROSPECTOR, and XCON, represent only the tip of the iceberg of the many impressive successes demonstrated by expert systems throughout the 1970s and 1980s. Since the mid-1980s, expert systems have been built by the thousands. They have been used in nearly every major industry sector for nearly every type of application where it is valuable to capture human expertise and distribute it to nonexperts to improve their performance. Most expert systems were small (less than 200 rules), although some, like XCON, contained over 10,000 rules. In the 1990s, the terminology changed from *expert system* to either *knowledge system* or *knowledge management system,* but the underlying technology has remained largely the same.

Backpropagation and Neural Networks

Since the 1950s, there have been several attempts to build AI computers by modeling the function of human brain cells (neurons). Some of the early attempts at this bordered on the edges of nonscientific sensational conjecture. A great deal of U.S. government research money was spent through agencies like the Defense Advanced Research Projects Agency (DARPA) in attempts to develop useful computing capabilities based on systems of electronic approximations of neurons. In 1969, Martin Minsky and Seymour Papert published a critical analysis of the approach of these various efforts, highlighting their limitations, with the result that virtually all government funding for such projects ceased. It was not until the development of backpropagation algorithms in the mid-1980s that this approach regained its place as a reputable endeavor. Backpropagation allows the network to "feedback" a portion of its error. When this feedback occurs, minor changes are made in the initial network causing the network to change in the direction away from the error. Hence, learning occurs. Through the successive processing of many data points, the network will converge on a configuration that will closely model the underlying process. In order to guarantee convergence, there are several parameters that must be properly initialized before the training begins. Getting these parameters set properly can be a very elusive goal for the novice.

There are many types of neural network approaches that do not use backpropagation. One of these that has achieved some popularity recently is the Hopfield neural network. However, most of the commercially useful neural net solutions do use backpropagation.

Modern neural networks are not actually very accurate models of how systems of neurons in the human brain work. They are better viewed as linear algebra models that, through the use of nonlinear error feedback (backpropagation), converge on a model that statistically represents the relationship between the inputs (or question) and the outputs (or conclusion). This error feedback and statistical convergence happens during the "training" period. Typically, a system is trained by providing it with large amounts of *real* (not simulated or speculative) data. As each new data point is entered, the system processes it, measures the error (error = expected output – actual output), and then automatically feeds a portion of the error back to adjust the coefficients of the linear algebraic matrix being used to model the relationship between the inputs and the output. The advantages of this approach are that, in time, the model *might* converge on a statistically accurate representation of the relationship and thereby discover the empirical relationships that were previously unknown to human experts. Once convergence occurs (or is suspected), the trained network needs to be tested with real data that was gathered from the process but was included in the training data set—data that the network has not yet seen. In this way, one can avoid false convergence because the network has not actually converged on the underlying relationships of the process, but instead has simply "memorized" the data in the training set.

The major drawback of neural nets is that there are usually such large amounts of data required that the time and expense of collecting the necessary data are often prohibitive. A serious neural network project is not for novices. A thorough and practiced understanding of the issues that characterize empirical modeling, and the proper selection and adjustment of the backpropagation parameters, would help to improve the chances of success. Nevertheless, some impressive successes have been demonstrated using neural networks in the areas of security sensor systems, remote sensing of minerals, tactile sensor imaging, airport security, infrared signature analysis, adaptive signal processing, automatic parts selection on assembly lines, sonar target classification, just to name a few. For more information on neural networks, the reader is referred to the neural network case study presented by Laura Burke in Chap. 11.6.

EXAMPLES OF EXPERT SYSTEMS IN USE IN THE IE AND RELATED COMMUNITIES

Methods Engineering/Work Measurement Focus: An Expert System to Develop Shuttle Ground Processing Metrics

John F. Kennedy Space Center (KSC) industrial engineers are using expert systems to identify techniques to improve the efficiency and effectiveness of space shuttle ground processing. This is being accomplished by measuring shuttle ground process efficiency. Although many work measurement techniques and methodologies are best suited to short-duration, highly repetitive activities, there are approaches to successfully measure the work time associated with long-duration, low-repetition tasks like those inherent in shuttle ground processing.

A challenge to work measurement practitioners is that there is no guidance as to which of several available measurement techniques should be used. Practitioners must rely on their own experience, on-the-job training, previous approaches used by their predecessors in the organization, or trial and error. This method of choosing a work measurement technique can lead to ineffective results and wasted effort. KSC industrial engineers have recognized this deficiency and have begun to research ways to fill the void.

In 1994, KSC industrial engineers and their support contractors began to develop an expert system to help the practitioner make informed decisions about which work measurement technique is best for the situation at hand. The expert system, designed for the IBM PC platform, asks the practitioner a series of questions about issues relevant to technique selection. The expert system uses answers provided by users to navigate through the relevant issues while helping users select a practical work measurement technique for their application. The system considers many attributes of the problem, including precision requirements of the final result, critical path considerations, task duration, visual accessibility, workforce participation considerations, and cost and benefit expectations. By using this expert system, inexperienced as well as experienced practitioners better understand the issues, make better decisions, and better understand the impact of their work measurement technique selection decisions.

Key Accomplishments:

- 1994—Successfully demonstrated the prototype expert system to select an appropriate work measurement technique (see Fig. 12.5.1).

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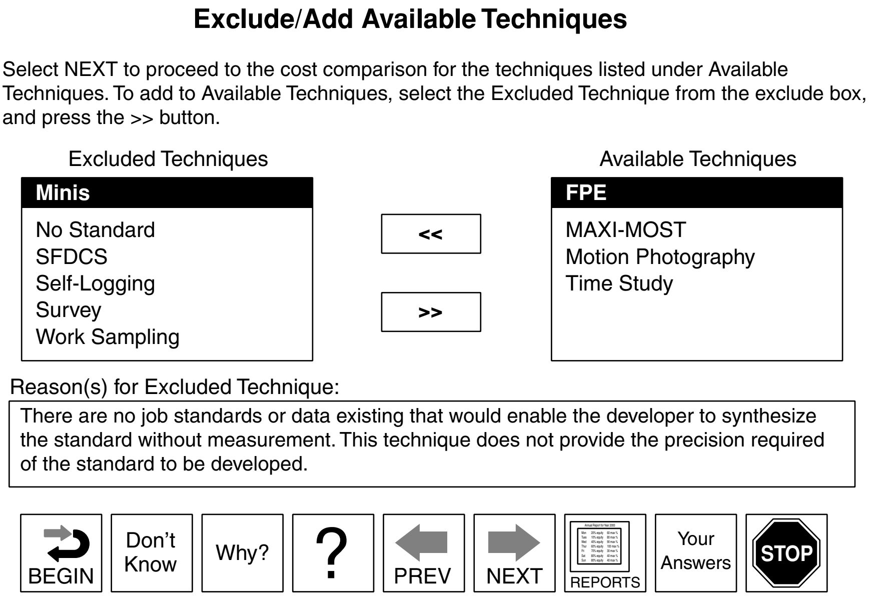

Exclude/Add Available Techniques

Select NEXT to proceed to the cost comparison for the techniques listed under Available Techniques. To add to Available Techniques, select the Excluded Technique from the exclude box, and press the >> button.

Excluded Techniques	Available Techniques
Minis	FPE
No Standard	MAXI-MOST
SFDCS	Motion Photography
Self-Logging	Time Study
Survey	
Work Sampling	

Reason(s) for Excluded Technique:

There are no job standards or data existing that would enable the developer to synthesize the standard without measurement. This technique does not provide the precision required of the standard to be developed.

FIGURE 12.5.1 Available techniques based on user input.

- 1996—Conducted small-scale test of a work measurement technique in KSC environment.
- 1997—Conducted comprehensive field trial of the work measurement technique that was tested in 1996.
- 1998—Tested and installed the Job Standards Development System (JSDS). The JSDS includes expert systems to select the work measurement techniques, guide the work measurement, and compute the job standard.

ENERGEX: An Expert System for Determining Industrial Energy Efficiency

Manufacturing must extract the highest percentage of productive energy from each Btu of energy produced, especially since it has a high per capita consumption of energy in the industrial sector. This is necessary for competing in the global marketplace. ENERGEX is an expert system that has been developed by West Virginia University's Industrial Engineering Department to aid industrial engineers in developing energy conservation opportunities (ECOs) in plants. The expert system is capable of recommending ECOs in areas such as lighting, boilers, motor selection, analysis of belt-driven systems, destratification, insulation of heated surfaces, and air compressor operation. In addition, the expert system offers expert advice on all these areas including power factor improvement possibilities. The expert system has been designed to query the industrial user on aspects related to the plant, from which the most appropriate ECO list is generated and presented for further analysis.

Most manufacturing processes are energy intensive, and U.S. manufacturers are some of the world's major consumers of energy. In the United States, 60 percent of total costs in the oil refining and distilling industry are energy costs, 40 percent in cement works are energy costs, and 25 percent of total costs in paper manufacturing can be traced to energy consumption. Concerns about energy efficiency in U.S. manufacturing prompted the U.S. Department of Energy's (DOE) Office of Industrial Technologies in the Department of Energy Efficiency and Renewable Energy to establish the Energy Analysis and Diagnostic Center (EADC) in 1976. Upon request from qualifying small manufacturers, the EADC will conduct energy audits of small businesses' manufacturing operations, observing and determining the amount of energy used in processes and by individual pieces of equipment and support services.

To qualify for an energy audit, the manufacturer must meet certain criteria that define it as a small business; these criteria include limitations on gross annual sales, number of employees, and annual energy-consumption costs. Additionally, the business must be within 150 miles of a university that conducts the audits and it cannot have a technical staff of its own that is qualified to conduct the energy analysis.

In fiscal year 1994, the National Research Center for Coal and Energy (NRCCE) awarded an Energy and Environmental Research Enhancement grant to West Virginia University's Industrial Engineering Department for the purpose of developing an expert system (ENERGEX) that would allow more manufacturers to conduct their own energy audits easily and inexpensively. ENERGEX is a PC-based expert system that allows businesses that are ineligible for an EADC audit to conduct the audits themselves with the expert knowledge of the EADC auditors built into the software package. The program can sort through audit data and identify equipment and processes that use excessive amounts of energy. Once these ECOs are identified, the program provides the user with probable causes for the extreme energy consumption and suggestions for implementing changes that will result in less energy use and higher efficiency. The company can obtain a fairly accurate estimate of the cost savings, the energy savings, the implementation cost, and the economic payback associated with implementation of the suggested modifications. And, with the expert system, audits are not a one-time thing; they can be conducted many times as facilities monitor changes to their operations and input new data for analysis.

ENERGEX queries the user for information about the plant in general. From this basic information, the user is informed of the nature of energy conservation opportunities present in the plant and can then choose any ECO and obtain further details regarding analysis and energy-saving implementations. Once the user chooses a particular ECO, he or she is presented with a series of questions pertaining to that particular ECO.

ENERGEX has been developed to address ECOs associated with boilers, motors, destratification, belt-driven systems, insulation of surfaces, and compressors. According to the expert system's designer, Bhaskaran Gopalakrishnan of WVU's IE department, "When plants can bring energy assessment in-house and conduct assessments on a routine basis, energy use will become more and more efficient. In light of our ever-growing energy demands, energy efficiency is beneficial not just to the economy and to individual operations that are saving money by cutting their energy consumption, energy efficiency is important to the entire nation because it helps us conserve our energy resources" [4].

In ENERGEX, a production rule-based system, the knowledge is presented as if-then rules, which exhibit the connection between conditions and conclusions in "and" and "or" relationships. The system uses backward chaining to arrive at conclusions. In backward chaining, one begins with a goal state and searches the knowledge-base for data to substantiate it. The inference engine searches from rule to rule until it is able or unable to substantiate the conditions required for proving the existence of the goal state.

Pollution Reducing Options in Processes: An Efficacy Ranking Method

Industrial processes usually produce emissions of pollutants to the environment. Emission standards and high emission charges force producers to control these emissions. This could be done by either concentration and destruction of the substances, or by a more preventive method like using cleaning technologies as part of the production process.

PROPER (Pollution Reducing Options in Processes: an Efficacy Ranking method) is an expert system that chooses an appropriate combination of cleaning technologies for a set of wastewater streams. The program makes its selection of cleaning technologies based on the efficiency of removal of technologies. In principal the program deals with converting networks of wastewater streams: the individual wastewater streams unite, resulting in just one stream. This stream contains the sum of all the wastewater streams in the network. Streams cannot be recycled inside the network.

The contents of a wastewater stream is characterized by properties and pseudocompounds. Properties of wastewater stream are temperature, pressure capacity, pH-value. A pseudocompound is a group of components in the stream, with an identical chemical and physical behavior.

In PROPER, the wastewater streams are characterized by pseudocompounds. Wastewater streams can consist of more than one pseudocompound. In this way the characterization of a wastewater stream is more general than if described with components, but specific enough for the selection of cleaning technologies. The division into pseudocompounds has to be done by the user of the program. The user decides how many pseudocompounds are needed to describe the wastewater stream. The list of properties of pseudocompounds is standard. For every pseudocompound, the user fills in what properties are present, keeping in mind that all the components contained in that pseudocompound should fulfill this property. Once these initial user selections are made, the PROPER expert system then selects the appropriate technologies for a given wastewater stream or network of waste streams.

Other Examples of Expert Systems in Manufacturing

Expert systems are used by the General Motors Corporation to assist in diagnosing problems in manufacturing equipment, anticipating failures, and scheduling repairs and preventive maintenance. Expert systems facilitate the distribution of the expertise of GM's best technicians. This means that even novice diagnosticians can perform at the level of an expert with many years of experience.

Boeing uses an expert system to help employees make decisions regarding the proper assembly of complex electrical connectors and cables for airplane manufacturing, maintenance, and repair. The Boeing system uses a very large rule-base comprising more than 25,000 rules.

Texas A&M University developed an expert system to aid Chrysler engineers in the design of cooling systems for automobiles. This expert system generates the design specifications for the cooling system of a vehicle from a description of the subsystems, engine, air conditioning, and transmission that determines the cooling requirements for the vehicle. The expert system allows designers to quickly analyze several alternative designs for the purpose of choosing the most cost-effective solution for a particular design problem.

SUMMARY

Expert systems have firmly entrenched themselves and are steadily becoming a mainstream information system technology of particular use to the industrial engineering community. The visibility, and even hype, that once accompanied an expert system proposal has, for the most part, passed. In its place is a steady, reliable workhorse. Expert systems will no doubt continue to grow in importance and value to the industrial engineering community.

Neural network solutions have not yet succeeded in claiming mainstream status particularly in the IE arena. As sophisticated data collection mechanisms increase in the manufacturing industry, and as manufacturing processes continue to become more complex, the importance and value of neural networks will likely expand.

Other newer artificial intelligence technologies such as intelligent data mining and genetic algorithms have yet to establish their practical usefulness. Impressive controlled and laboratory successes have been demonstrated. Careful and cautious application of these newer technologies may eventually prove to be of significant benefit in the industrial engineering workplace.

ACKNOWLEDGMENT

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BIOGRAPHY

Richard L. Routh is currently the president of The GINESYS Corporation—an Internet knowledge systems company that specializes in building business solutions with expert system

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SECTION 13

PRODUCT DESIGN AND QUALITY MANAGEMENT

CHAPTER 13.1

PRODUCT DEVELOPMENT

Jack M. Walker
The Jack Walker Group
Merritt Island, Florida

The industrial engineer's functions in the general field of product development, along with the teamwork process among the various factory functions during the actual design and development phase of a product, are the contents of this chapter. Consideration of the customer's wants and needs, the company's position in relation to the competition, and the relative costs and producibility of the various options are key elements. Rapid prototyping techniques allow design concepts to be produced quickly in support of product development—and may aid in production start-up prior to availability of the planned "hard" tooling.

BACKGROUND

It is not enough today for a product to only perform its intended function—this is the minimum expected! The product must also be capable of being produced of the required quality, cost, rate, and in the time available—with features as demanded by customers. Between 70 and 90 percent of the final product cost and difficulties in production are a direct result of design decisions. To ensure that the processes dictated by the design are repeatable and controllable, the manufacturing system must be developed concurrently with the product development.

In an increasing number of companies around the world, both the product designer and the process developer are climbing over the wall that used to separate the two disciplines. A team of development-related functions should participate in the design of a new product, or the improvement of an existing product. It does not matter whether we call the concept concurrent engineering, integrated product definition, or simultaneous engineering, as long as we consistently produce high-quality products on time for the best price.

There are tools, systems, and specialty companies available to formalize the product development process for products that will make money for the company and satisfy the customer. There are also rapid prototyping techniques that allow design concepts to be produced quickly to assist in product development—and in production start-up prior to availability of the planned "hard" tooling.

CONCURRENT ENGINEERING

Introduction

What is *concurrent engineering* (CE)? Agreeing on a common definition helps communication and understanding. The Department of Defense/Institute of Defense Analysis (DoD/IDA) definition has wide acceptance. IDA Report R-338 gives the following definition:

> Concurrent engineering is a systematic approach to the integrated, concurrent design of products and their related processes, including manufacture and support. This approach is intended to cause the developers, from the outset, to consider all elements of the product life cycle from conception through disposal, including quality, cost, schedule, and user requirements.

Four main elements have emerged as most important in implementing CE: (1) the voice of the customer, (2) multidisciplinary teams, (3) automated tools, and (4) process management. The underlying concept is not a new one: *teamwork*. The secret is to involve all the right people at the right time. We must increase our understanding of product requirements by being more effective in capturing the "voice of the customer." We must increase our emphasis on product producibility and supportability. This requires the involvement of all related disciplines on our CE teams. We must acquire and use the best tools to permit the efficient development of build-to technical data packages. Finally, we must increase our emphasis on developing production processes in parallel with development of the product.

Why CE?

By collecting and understanding all requirements that the product must satisfy throughout its life cycle at the start of concept definition, we can reduce costs, avoid costly redesign and rework, and shorten the development process. We do this by capturing the customer requirements and expectations, and involving all related factory disciplines from the start. Working as teams on all product-related processes, we can provide for a smooth transition from development to production. Experience shows that CE results in the following:

- Well-understood user requirements
- Reduced cycle times
- First-time quality with producible designs
- Lower costs
- Shorter development spans
- A smoother transition to production
- A new respect for other teammates
- Highly satisfied customers

Concurrent engineering pays off in the following ways:

- Product development cycle time is reduced between 40 and 60 percent
- Manufacturing costs are reduced between 30 and 40 percent
- Engineering change orders are reduced more than 50 percent
- Scrap and rework are reduced by as much as 75 percent

The primary elements of CE include:

- Voice of the customer
- Multidisciplinary teams
- Automation tools and techniques
- Process management

The voice of the customer includes the needs and expectations of the customer community, including end users. Concurrent engineering can best be characterized by the conviction that product quality can be achieved only by listening and responding to the voice of the customer. The ideal way is to capture, at the outset, all requirements and expectations in the product specifications.

One effective way to accomplish this is to conduct focus group sessions with different elements of the customer's organization. Properly staffed multidisciplinary teams provide the means to enable all requirements, including producibility and supportability, to be an integral part of product design from the outset. (See Fig. 13.1.1.) Concurrent engineering teams are broadly based, including representatives from design engineering, production, customer support, procurement, quality assurance, business systems, new business and marketing, and suppliers. Broadly based CE teams succeed because they can foresee downstream needs and build them into our products and processes. Not all team members are necessarily full-time. In many cases, part-time participation is all that is needed and all that can be afforded. Smaller companies and simple products will dictate a small team—although the functions remain the same!

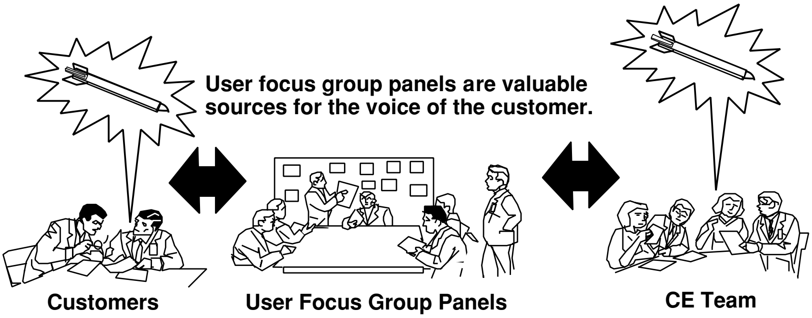
User focus group panels are valuable sources for the voice of the customer.
Customers
User Focus Group Panels
CE Team

FIGURE 13.1.1 Translating customer requirements into requirements for the designer. *(Courtesy of Technicomp, Inc., Cleveland, OH.)*

Automation tools and techniques provide effective and efficient means of developing products and services. Solid modeling design tools can be used as electronic development fixtures (EDFs) during prototyping, in lieu of mock-ups, to verify clearances and mechanism operations before hardware is fabricated.

Process management is the final key to controlling and improving the organization, as well as the processes used to develop, build, and support a product. This is probably the newest and least practiced element of CE. Big gains can be made by defining the program work flows and processes and then improving them. Processes define the relationships of tasks and link the organization's mission with the detailed steps needed to accomplish it. Program-wide processes provide a means of identifying the players who need to be involved and also indicate team interrelationships. Product processes are also a part of process management, requiring the definition and development of production processes in parallel with the definition and development of the product design. Companies that are ISO 9000 registered find that this product process definition step is required to certify and maintain their ISO status.

CE Throughout the Acquisition Process

Concurrent engineering practices are applicable to all programs, old or new, regardless of program type or acquisition phase. The biggest payoff is made by implementing CE at the very beginning of a program. Because most of a product's cost is determined during the concept phase, it is very important to have manufacturing, producibility, supportability, and suppliers involved then.

The Voice of the Customer

The voice of the customer (VOC) represents the needs and expectations by which the customer or user will perceive the quality of products and services. Quality is achieved by satisfying all customer needs and expectations—technical and legal documentation will not overcome bad impressions. Meeting the minimum contractual requirements will often not be enough, especially in a highly competitive environment. Customer quality expectations invariably increase based on exposure to other best-in-class products and services. Nevertheless, the products and services must be provided consistent with contractual requirements and within the allotted budgets. This is not an easy task—it requires continuous attention and good judgment to satisfy the customer, while staying within program constraints.

Requirements definition begins at the program's inception and continues throughout the product life cycle. It is essential that the right disciplines, including suppliers, are involved at all times in order to avoid an incomplete or biased outcome.

CE USING THE QUALITY FUNCTION DEPLOYMENT SYSTEM

Introduction to Quality Function Deployment

Quality function deployment (QFD) is one of the formal commercial systems for aiding a company in this complex process of developing a new or revised product using CE philosophy. It provides a structure for ensuring that customers' wants and needs are carefully heard, then translated directly into a company's internal technical requirements—from component design through final assembly. Quality function deployment is defined as "a *discipline* for product planning and development in which key customer wants and needs are deployed throughout an organization."

Quality. What the customer/user needs or expects

Function. How those needs or expectations are to be satisfied

Deployment. Making it happen throughout the organization

The program utilizes a series of matrices, starting with the customer *wants* on one axis and the company's technical interpretation of how to accomplish these customer expectations on the other axis. These elements are weighted and quantified, to permit focus on the most important issues, or on the areas where the company product is most deficient. Quality function deployment starts with the VOC. Using all practical means, the team gathers customer needs and expectations. The team has to analyze these inputs carefully to avoid getting caught up in providing what they *expect* or *believe* that the customer needs.

Background of QFD

Technicomp, Inc., of Cleveland, Ohio, developed QFD. The first application as a structured discipline is generally credited to the Kobe Shipyard of Mitsubishi Heavy Industries Ltd. in 1972. It was introduced to the United States in a 1983 article in *Quality Progress,* a publication of the American Society of Quality Control (ASQC). U.S. companies that have utilized QFD include Alcoa, Allen-Bradley, Bethlehem Steel, Boeing, Caterpillar, Chrysler, Dow Chemical, General Motors, Hexel, Lockheed, Magnavox, and others. The program consists of a series of videotapes, team member application guides, instructor guides, and other course materials.

Project Team Membership

Management commitment to QFD is the minimum requirement; support by the entire organization is ideal. Participation on a project team is required by individuals who support QFD and who represent all development-related functions, such as:

- Design engineering
- Process engineering
- Marketing and sales
- Manufacturing engineering
- Quality assurance
- Procurement

Strength of Utilizing QFD

- QFD helps minimize the effects of
  - Communication problems
  - Differences in interpretation about product features, process requirements, or other aspects of development
  - Long development cycles and frequent design changes
  - Personnel changes
- QFD provides a systematic means of evaluating how well you and your competitors meet customer needs, thus helping to identify opportunities for gaining a competitive edge (sort of minibenchmarking).
- QFD brings together a multifunctional group very early in the development process, when a product or service is only an idea.
- QFD helps a company focus time and effort on several key areas, which can provide a competitive edge.

Potential Benefits

Companies that have implemented QFD have reported the following results:

- Between 30 and 50 percent reduction in engineering changes
- Between 30 and 50 percent shorter design cycles
- Between 20 and 60 percent lower start-up costs
- Between 20 and 50 percent fewer warranty claims

Phases of QFD

Quality function deployment involves a series of phases (see Fig. 13.1.2) in which customer requirements are translated into several levels of technical requirements. Phases are often documented by a series of linked matrices:

- *Phase 1—product planning.* Customer requirements are translated into technical requirements or design specifications in the company's internal technical language.
- *Phase 2—product design.* Technical requirements are translated into part characteristics.
- *Phase 3—process planning.* Part characteristics are translated into process characteristics.
- *Phase 4—process control planning.* Process characteristics are assigned specific control methods.

The House of Quality

The QFD program introduces a chart, commonly called the *House of Quality.* In very simple terms, the house of quality can be thought of as a matrix of *what* and *how:*

- *What* do customers want and need from your product or service? (*customer requirements*)
- *How* will your company achieve the *what?* (*technical requirements*)

The matrix shows where relationships exist between *what* and *how,* and the strength of those relationships. Figure 13.1.3 is a simplified example for large rolls of paper stock used in commercial printing. Following is a brief summary of the completed chart:

(A) *Customer requirements.* Customers' wants and needs, expressed in their own words.

(B) *Technical requirements.* Design specifications through which customers' needs may be met, expressed in the company's internal language.

(C) *Relationship matrix.* Indicates with symbols where relationships exist between customer and technical requirements, and the strength of those relationships.

(D) *Target values.* Show the quantifiable goals for each technical requirement.

(E) *Importance to customer.* Indicates which requirements are most important to customers.

(F) *Importance weighting.* Identifies which technical requirements are most important to achieve. In this chart, each weighting is calculated by multiplying the "importance to customer" rating times the value assigned to a relationship, then totaling the column.

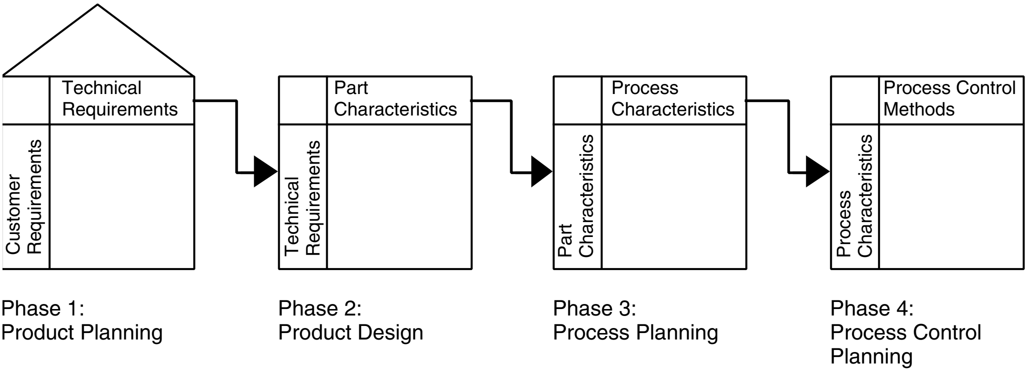
Technical Requirements
Customer Requirements
Part Characteristics
Technical Requirements
Process Characteristics
Part Characteristics
Process Control Methods
Process Characteristics
Phase 1: Product Planning
Phase 2: Product Design
Phase 3: Process Planning
Phase 4: Process Control Planning

FIGURE 13.1.2 The four phases of quality function deployment (QFD). *(Courtesy of Technicomp, Inc., Cleveland, OH.)*

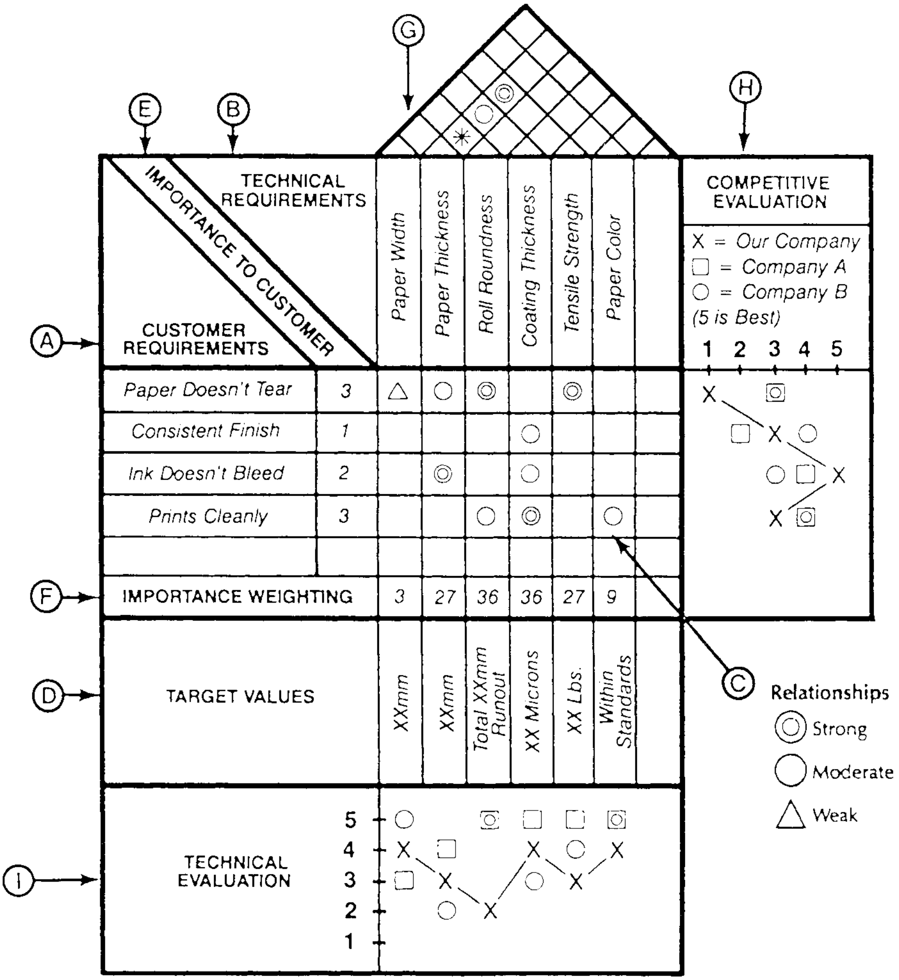
G
E
B
H
TECHNICAL REQUIREMENTS
IMPORTANCE TO CUSTOMER
CUSTOMER REQUIREMENTS
A
Paper Width
Paper Thickness
Roll Roundness
Coating Thickness
Tensile Strength
Paper Color
COMPETITIVE EVALUATION
X = Our Company
□ = Company A
○ = Company B
(5 is Best)
1 2 3 4 5
Paper Doesn't Tear
3
Consistent Finish
1
Ink Doesn't Bleed
2
Prints Cleanly
3
F
IMPORTANCE WEIGHTING
3
27
36
36
27
9
C
Relationships
Strong
Moderate
Weak
D
TARGET VALUES
XXmm
XXmm
Total XXmm Runout
XX Microns
XX Lbs.
Within Standards
I
TECHNICAL EVALUATION
5
4
3
2
1

FIGURE 13.1.3 Quality function deployment's house of quality for rolls of paper stock. *(Courtesy of Technicomp, Inc., Cleveland, OH.)*

(G) *Correlation matrix.* Indicates with symbols where relationships exist between pairs of technical requirements, and the strength of those relationships.

(H) *Competitive evaluation.* Shows how well a company and its competitors meet customer requirements, according to customers.

(I) *Technical evaluation.* Shows how well a company and its competitors meet technical requirements.

Product Planning (Phase 1 of QFD)

Most companies begin their QFD studies with the product-planning phase, which involves activities including collecting and organizing customer wants and needs, evaluating how well your product and competitive products meet those needs, and translating those needs into your company's specific technical language. At this point, the house of quality contains enough information for you to choose several key technical requirements on which to focus additional planning and definition. As a general rule, especially for pilot QFD projects, limit the number of key requirements to between three and five. Those with the highest importance or relative weights are good candidates. They should have a strong bearing on satisfying the highest-priority customer requirements, or many of the customer requirements. However, don't look at just the numbers when choosing the key technical requirements. Also consider:

- Potential difficulty of meeting a requirement
- Any technical breakthroughs that may be needed
- Requirements that are unfamiliar to your company

These factors can be particularly important if you must choose key requirements from several that have similar weightings.

Goals Definition

Before starting a chart, the scope and goals of the study must be clearly identified. A typical chart enables you to:

- Learn which requirements are most important to customers
- Spot customer requirements that are not being met by technical requirements, and vice versa
- Compare your product or service with the competition
- Analyze potential sales points
- Develop an initial product or service plan

Many U.S. companies complete only the first phase of QFD in their studies. A QFD study should proceed beyond phase 1, into phase 2 if any of the following are true:

- Product or service requires more or better definition.
- Additional detail is needed to make significant improvements.
- Technical requirements shown on the house of quality cannot now be executed consistently.

Product Design (Phase 2)

The series of matrices used in QFD now come into play. The technical requirements, which were shown across the top of the House of Quality chart in Fig. 13.1.3, now become the left margin of the product design chart, as shown in Fig. 13.1.4. Across the top of the matrix in phase 2 are the design part characteristics required to meet the technical requirements. An evaluation of these is made, and they, in turn, become the left margin of phase 3, process planning. This series of matrices is the key feature of the QFD system, and it has proven to be very effective in the development of any product or service.

The overall goal of phase 2 is to translate key technical requirements from the house of quality into specific parts characteristics. *Parts* are tangible items that eventually compose the product or service—its elements, raw materials, or subsystems. Inputs to this phase are:

- Highest-priority technical requirements from phase 1
- Target values and importance weights for those requirements
- Functions of the product or service
- Parts and mechanisms required

PRODUCT DEVELOPMENT

			Mechanism									Mechanism									Mechanism								
			Part			Part			Part			Part			Part			Part			Part			Part			Part		
Key Technical Requirements (TR)*	TR Target Values	TR Importance Weights	Part Characteristic	Part Characteristic	Part Characteristic	Part Characteristic	Part Characteristic	Part Characteristic	Part Characteristic	Part Characteristic	Part Characteristic	Part Characteristic	Part Characteristic	Part Characteristic	Part Characteristic	Part Characteristic	Part Characteristic	Part Characteristic	Part Characteristic	Part Characteristic	Part Characteristic	Part Characteristic	Part Characteristic	Part Characteristic	Part Characteristic	Part Characteristic	Part Characteristic	Part Characteristic	Part Characteristic
PC Importance Weights																													
PC Target Values																													

*TR, technical requirement; PC, part characteristic.

FIGURE 13.1.4 Product design matrix used to identify key-part characteristics and to select best design concepts. *(Courtesy of Technicomp, Inc., Cleveland, OH.)*

The outcome of the product design phase is the identification of key part characteristics, and the selection of the new or best design concepts.

RAPID PROTOTYPING

Background

One of the goals of all successful companies is to reduce the time between initial concept of a product and production deliveries. The other vital concept is the early involvement of manufacturing expertise with the product design team. This includes outside suppliers along with in-house experts. The outside suppliers that must be involved are those trades and skills involving parts that your company may buy rather than build in-house. This may include castings, forgings, plastic moldings, specialty sheet metal, electronics, or machining. Their knowledge can assist the original equipment manufacturer (OEM) to produce a better product, in a shorter time, at a lower cost. They may also produce the early production parts while you are waiting for your hard tooling to be completed. They may even be your eventual production supplier, or a backup source if your production supplier has problems.

Often, the small details of a part or process can greatly influence the design. In the product design and development phase of a project, it is often valuable to have a prototype part made of a proposed design, or of alternative designs, to permit members of your team to get a better feel for the design concept. In the automobile industry, for example, the appearance and feel of doorhandles, controls, and the like are important to the ultimate customer. We can look at drawings or computer screens of a concept design, but few of us can assess what a Shore Durometer hardness number means on paper as well as we can by handling several versions of a part with different flexibility, color, or made from different materials. Most good designs are an iterative process, and many companies do not have the in-house capability to quickly make accurate prototypes in their production shops. A prototype part is more than a model. It is as much like the eventual production part as possible—in a short period of time!

Rapid prototyping is one of the names given to a new group of technologies for converting designs from computer representations directly into solid objects without human intervention. No single one of the many technologies has yet proven that it can meet all market requirements, so those intending to be involved in this industry should know the fundamental processes, limits, and potentials of the competing machines.

There are several specialty companies in the United States that have the ability to produce models and patterns using the latest rapid prototyping techniques, including stereolithography (SLA), laminated object manufacturing (LOM), selective laser sintering, CAM hog-outs from solid stock, as well as traditional pattern making and craft skills for producing prototype plaster-mold metal castings and plastic parts. Some specialize in photoetching metal blanks, others in quickly producing sheet-metal parts with temporary, low-cost tooling. Complex investment castings can be made without tooling. With these skills and methods, these companies can create premium-quality, economical parts in the shortest time possible. Whereas two or three weeks is fairly common lead time, they sometimes can deliver prototype parts in less than one week.

Many of these companies can produce parts directly from CAD files, as well as from drawings or sketches. This allows us to send data via modem, rather than relying on other communication systems. For example, Armstrong Mold Company, in East Syracuse, New York, uses IGES, DFX, CADL, and STL file formats directly, or they can work from floppy disk or DC 2000 mini–data tape cartridges to produce prototype parts with short lead times.

Advantages of Rapid Prototyping

- Manufacture without paper—work directly from CAD files or sketches
- Produce functional parts as quickly as one week
- Produce models that can be used as masters for making metal castings and plastic parts in small or large quantities
- Use fit-and-function models to detect design flaws early in development
- Allow prototype part to be used during qualification testing of a product

Prototype Parts Using Stereolithography

Stereolithography (SLA) is used to create three-dimensional objects of any complexity from computer-aided design (CAD) data. Solid or surfaced CAD data is sliced into cross sections. A laser generating an ultraviolet beam is moved across the top of a vat of photosensitive liquid polymer by a computer-controlled scanning system. The laser draws each cross section, changing the liquid polymer to a solid. An elevator lowers the newly formed layer to recoat and establishes the next layer thickness. Successive cross sections are built layer by layer one on top of another, to form a three-dimensional plastic model. Armstrong, along with several other firms, takes advantage of this process.

An interesting development of SLA is the addition of metallic particles to the matrix. The prototype part can then be heated (*sintered*), removing the resin and fusing the part to provide the near equivalent of a metal casting.

Laminated Object Manufacturing

Laminated object manufacturing (LOM) is also used to create three-dimensional objects of any complexity from CAD data. Solid or surfaced CAD data is sliced into cross sections. A single laser beam cuts the section outline of each specific layer out of 0.05- to 0.5-mm- (0.002- to 0.020-in-) thick paper that has been precoated with adhesive. A second layer is then bonded to the first, and the trimming process is repeated. This process continues until all layers are cut and laminated, creating a three-dimensional, multilayered, woodlike model. One LOM machine observed had a 810 × 560 × 510 mm (32 × 22 × 20 in) working envelope.

Materials other than paper are now available for the LOM process. Recent developments in the thickness of the adhesive used has permitted greater accuracy of the finished parts.

Machined Prototypes

Three-dimensional objects can be cut from a variety of solid stocks (metal, resin, plastic, wood) directly from two- or three-dimensional CAD data using multiaxis CNC machining centers. Applicable machines can be utilized for making models from drawings or sketches. Although this process has not had the publicity of some of the more sophisticated systems, it remains as one of the first choices in producing prototype parts.

Casting Metal Parts Using Plaster Molds

Aluminum or zinc castings can be produced by pouring liquid metal into plaster (gypsum) molds. Typical applications at Armstrong include:

- Castings for business machines, medical equipment, computers, automotive, aerospace, and electronics
- Molds for the plastics industry: rotational, vacuum-form, expanded polystyrene, kirksite, and injection molds

The first step in the process is to make a model or master pattern. This can be done from a drawing or CAD file. The material can be wood, plastic, or machined from brass or other metal. The model is either hand-crafted or machined, using multiaxis CNC or toolroom machines, depending on the complexity and availability of CAD data. The model will have shrinkage factors built in, as well as draft, and machining allowance if desired. A customer-furnished model or sample part can by adapted to serve as the master pattern (see Fig. 13.1.5).

The second step is to make a negative mold, and core plugs if required, from the master model. A positive resin cope-and-drag pattern is now made from the negative molds. Core boxes are built up, and the gating and runnering system, with flasks as necessary, are added.

Next, a liquid plaster slurry is poured around the cope-and-drag pattern and into the core boxes. After this sets, the plaster mold is removed from the cope-and-drag patterns. The plaster mold and cores are then baked to remove moisture.

Molten metal is prepared by degassing, and spectrographic analysis of a sample checks the chemical composition of the material. The molten metal is then poured into the assembled plaster mold. When the casting has cooled, the plaster is removed by mechanical knockout and high-pressure water jet, and the gates and risers are removed.

The raw castings are then inspected and serialized. Any flash and excess metal is removed (snagged). Castings may then require heat treatment, x ray, or penetrant inspection as requested by the customer. After inspection, the casting is ready for machining, chemical film, chromate conversion, paint or special finishes, and assembly if required. The objectives of this process are the following:

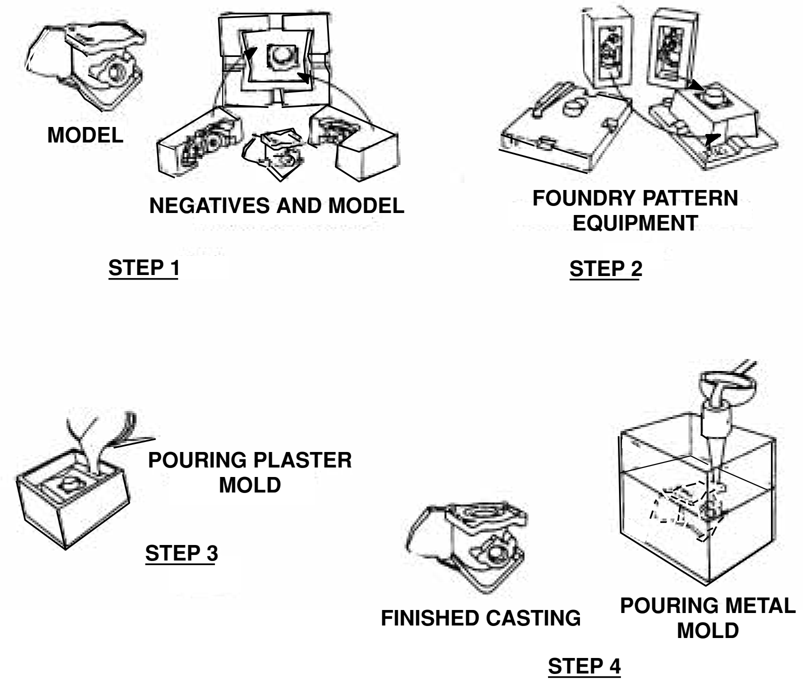
MODEL
NEGATIVES AND MODEL
STEP 1
FOUNDRY PATTERN EQUIPMENT
STEP 2
POURING PLASTER MOLD
STEP 3
FINISHED CASTING
POURING METAL MOLD
STEP 4

FIGURE 13.1.5 Plaster molding process. *(Courtesy of Armstrong Mold Corp., East Syracuse, NY.)*

- To produce precision and premium-quality aluminum and zinc castings.
- To apply aesthetics where appearance is critical.
- To prototype—to assist engineering in debugging design before committing to hard tooling. Parts may be used for testing.
- To apply complex or unusual shapes for low-volume applications.
- To apply complex or unusual shapes for high-volume applications.
- To allow for castings with thin walls or where weight is critical.
- To simulate die castings for prototype and pilot production.
- To make tooling low cost and allow for ease of modification.
- To reduce time to market on new programs and evaluate market potential.
- To reduce time for machining and secondary operations.
- To fill the gap if dies are lost, damaged, or delayed.

Design and Technical Information

Size. No limitation, but best range is within 50- to 900-mm (2- to 36-in) cube

Finish. Can hold 63 μin but normally 90 μin

Shape. Considerable design freedom for unusual and complex shapes

Wall thickness

- *Thin wall.* 7.5–15 mm (0.030–0.060 in)
- *Average.* 2–3 mm (0.080–0.120 in)
- *Thick.* 4.5–13 mm (0.180–0.500 in)

General tolerances

- 0–50 ± 0.25 mm (2 ± 0.010 in)
- 50–75 ± 0.3 mm (2–3 ± 0.012 in)
- 75–150 ± 0.38 mm (3–6 ± 0.015 in)
- 150–300 ± 0.5 mm (6–12 ± 0.020 in)
- 300–450 ± 0.75 mm (12–18 ± 0.030 in)
- 450–750 ± 1.0 mm (18–30 ± 0.040 in)

The process is limited to nonferrous metals with pouring temperatures below 1090°C (2000°F), which includes all aluminum and zinc casting alloys and some copper-based alloys. Aluminum and zinc casting alloys are per commercial and military specifications (see Fig. 13.1.6). This includes the appropriate mechanical properties. Small holes, 6.4 mm (¼ in) or less, are not economical to cast unless they are an odd shape or inaccessible for machining. Zero draft is possible in specified areas, but is typically ½° to 2°. Corner radii and fillets are as required, but are typically 1.5 mm (1⁄16 in) R.

A variety of models and patterns can be made, depending on the customer's request:

- *Wood.* To expedite for up to 20 pieces.
- *Epoxy resin.* Usually up to 500 pieces.
- *Metal (aluminum or brass).* Used to obtain best tolerances and quality.
- *Rubber.* For quantities up to 1000 pieces. Tooling can be duplicated easily from master tooling to expedite delivery or for higher volumes.

A rule of thumb for costs of complex shapes in 380-mm (15-in) cubes is:

- *Tooling.* 10 percent of die cost tools
- *Piece price.* 10 times die casting price

Normal delivery time is one to two weeks for simple parts, and six to eight weeks for complex parts.

Plaster- and Sand-Molding Combination

A combination of plaster and sand molding is used for castings that require high metallurgical integrity as verified by radiographic or fluorescent penetrant inspection. When used in combination with no-bake sand molds, the properties of plaster mold castings can be enhanced considerably by taking advantage of the faster cooling rates inherent in sand molds in combination with the insulating aspect of plaster molds. (Material still pours and fills, maintaining its liquidity, but then cools quickly.)

Investment Casting Metal Parts

Investment casting prototypes can be produced from plastic patterns without permanent tooling. In brief terms, the supplier replaces the wax pattern that would have been produced from an injection die with a low-melting-point plastic pattern assembled from multiple

		Mechanical properties					
Alloy	Heat treating	Ultimate tensile strength KSI	Min. yield strength set@ 2% KSI	Elongation % in 2°	Hardness Rockwell E scale 1/16-in ball	Pressure tightness[*]	Machinability[*]
319.0	T6	36	24	2.0	85.5	B	A
355.0	T51	28	23	1.5	76.0	A	C
355.0	T6	35	25	3.0	85.5	A	B
C355.0	T6	39	29	5.0	89	A	B
356.0	T51	25	20	2.0	71	A	C
356.0	T6	33	24	3.5	79	A	A
A356.0	T51	26	18	3.0	71	A	C
A356.0	T6	40	30	6.0	82.5	A	A
357.0	T51	26	17	3.0	80	B	C
357.0	T6	45	35	3.0	91	B	B
A357.0	T6	45	35	3.0	89	B	B
380.0	NONE	46	23	3.5	85.5	B	C
712.0[†]	[‡]	35[‡]	25[‡]	5.0[‡]	82.5	C	A
Zinc alloys[§]							
ZA3	NONE	41		10.0	87	C	C
ZA8	NONE	34	30	1.5	95.5	C	C
ZA12	NONE	43	30	2.0	9.3	C	B
ZA27	NONE	61	46	9.5	100	C	B

Applicable military specifications

- Mechanical/Chemical Inspection to MIL-A-21180 QQ-A-601, AMS-4217
- System Control to MIL-1-45208
- Gage Control to MIL-STD-45662
- Penetrant Inspection to MIL-STD-6866
- Radiographic Inspection to MIL-STD-453, MIL-STD-2175
- Heat Treat to MIL-H-6088
- N.D.T. to MIL-STD-410

[*] A, excellent; B, good; C, fair.
[†] 712.0 also known as D712, D612, and 40E.
[‡] Test 30 days after casting.
[§] These values are for separately cast test bars and are typical values.

FIGURE 13.1.6 Aluminum alloy casting mechanical properties. *(Courtesy of Armstrong Mold Corp., East Syracuse, NY.)*

pieces, or made by SLA. The assembly is then hand radiused with wax, and from this point on, the process continues in the same manner as the typical investment casting process. This gives the OEM the opportunity to qualify a casting as part of the initial testing program, eliminating the need for requalification had a machined part or a weldment been used as a substitute in qualification test hardware. Depending on the complexity of the design, the supplier can deliver a prototype investment casting in two weeks or so, at less cost than machining a part.

Castable Urethane Plastic Parts

Castable urethane is a liquid, two-component, unfilled urethane resin system that is poured into a closed mold. The result after solidification is a tough, high-impact-resistant, dimensionally stable part. This process is often used for the following:

- To produce prototype and low-volume plastic parts
- To simulate injection-molded parts to check fit and function, and to debug design
- To make molds from room-temperature-cure silicone (RTV) resin, sprayed metal, or, for precision parts, machined aluminum
- To make tooling low cost and allow for ease of modification
- To provide a variety of inserts that can be molded or post-installed
- To allow stereolithographic molds to be duplicated
- To allow for delivery to be from one to seven weeks after receipt of the order, depending on size and complexity

Design and Technical Information

Size. Up to 600 mm (24 in).

Wall thickness. Can vary but should be kept less than 74 mm (¼ in).

General tolerances

- 0–75 ± 0.25 mm (0–3 ± 0.010 in)
- 75–150 ± 0.38 mm (3–6 ± 0.015 in)
- 150–300 ± 0.5 mm (6–12 ± 0.020 in)
- 300–600 ± 0.75 mm (12–24 ± 0.030 in)

Draft. Recommended 1° to 2°, but no draft is possible if required.

Corner and filet radii. Can be sharp, but a radius of 74 mm (1⁄16 in) is preferred.

Reaction Injection Molding

In the *reaction injection molding* (RIM) process, two liquid components—component A, a formulated polymeric isocyanate, and component B, a formulated polyol blend—are mixed in a high-pressure head and then pumped into a mold cavity. A reaction then occurs in the mold, resulting in a high-density polyurethane structural foam part. This process has the following features:

- Can be used to produce covers, bases, keyboards, bezels, and housings for computers, business machines, and medical applications
- Allows prototype- through medium-volume applications (1 to 2000 pieces)
- Gives considerable design freedom to produce complex shapes
- Allows molds to be resin, sprayed metal, cast aluminum, or machined aluminum
- Makes tooling low cost and allows for ease of modification
- Allows for a variety of castings, sheet-metal, and threaded inserts to be molded in place
- Allows for alternative foams that are available, which offer a range of insulating properties
- Makes UL traceable

Design and Technical Information

Size. Up to 1200 mm (48 in).

Weight. Up to 8.2 kg (18 lb).

Wall thickness. Can vary, but should not be less than 6 mm (¼ in), although local thicknesses of 3 mm (⅛ in) can be produced.

General tolerances

- 0–75 mm ± 0.25 mm (0–3 in ± 0.010 in)
- 75–150 mm ± 0.38 mm (3–6 in ± 0.015 in)
- 150–300 mm ± 0.5 mm (6–12 in ± 0.020 in)
- 300–450 mm ± 0.75 mm (12–18 in ± 0.030 in)
- 450–1200 mm ± 1.0 mm (18–48 in ± 0.040 in)

Draft. Recommended 1° to 2°, but no draft is possible when specified.

Radii and fillets. Should be as liberal as possible—from 3 to 6 mm (⅛ to ¼ in).

Photochemical Machining

Photochemical machining (PC) allows burr-free, stress-free blanking on virtually all ferrous and nonferrous metal sheets with no chemical or physical alteration to the materials. With precise multiple imaging, multiple-parts blanks can be produced on sheets up to 750 mm (30 in) wide. The process can work with metals of any temper, with thickness ranging from 0.25 mm (0.001 in) to heavy gauge. The tolerance range is ±0.25 to ±2.5 mm (±0.001 to ±0.010 in), depending on material type and thickness. See Fig. 13.1.7 for some examples of parts made by this process.

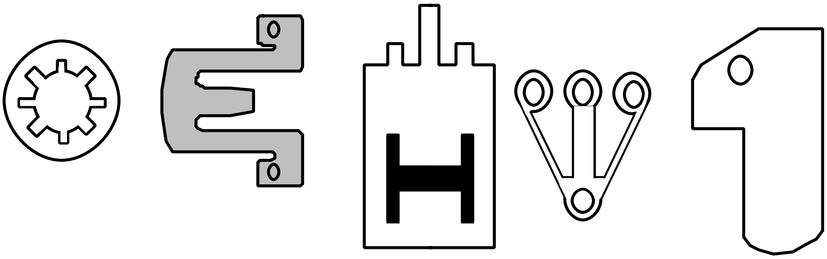

FIGURE 13.1.7 Examples of some parts made by photochemical machining. *(Courtesy of Microphoto, Inc., Roseville, MI.)*

The process starts with CAD drawings, either furnished by your company or made by the supplier. This is then copied multiple times to make a master negative containing the total parts required in the initial order, and checked for accurate registration. A metal sheet is sheared to size, cleaned, and coated with a photoresist. A contact print is made from the master sheet and developed. The entire sheet is then immersed in an acid bath and the unwanted metal is eaten away, leaving the finished part. The photoresist is then removed. This can then be followed by machining, forming, or whatever subsequent process is required.

Because tooling is produced photographically, lead time can be reduced from weeks to hours, and design changes can be made quickly, without scrapping expensive dies. Typical lead time is between one and two weeks using readily available materials, but this time can be shortened if the schedule demands it.

Short-Run Stampings

Tooling costs for short-run stampings are kept to a minimum. You share the tools and holders with all of the suppliers' customers. Standard round and square punches meet many demands. Standard forming tools make a wide variety of shapes. Design changes are most easily incorporated with short-run tooling. This minimizes costly scrap and retooling. Short runs do not create unnecessary penalties in either quality or cost.

The quality of stamped parts is usually more reliable than from most other methods. The part-to-part repeatability is unusually good. A good firm's quality control department will be well equipped to assure that your parts meet print/specifications.

Conclusions and Future Trends

The role of the industrial engineer, manufacturing engineer, process engineer, tool engineer—by whatever name has evolved over the years—will continue to play an even more important role in the design and production of future products. Concurrent engineering, as we define it today, will also be subject to change. The gray line between product design and production operations will continue to fade. We see many cases today where the order of development for new products has reversed—starting with the customer, moving to the production departments, and committed to firm drawings as the final step. This trend will continue.

The rapid prototyping field has seen even more changes. The last few years have seen the processes change from very costly laboratory models to techniques that produce parts of truly production quality, with a great reduction in cost. This is due, in part, to the faster processors, increased memory, and the ease of file transfer via the Internet. Early processes required the use of a mainframe computer, then a minicomputer, whereas most processes today are developed for a PC. Originally, parts were limited in the materials that could be utilized, whereas today we can make prototype products from a great many different materials, including metals that closely replicate production castings. Utilization of CNC machining, computer-generated tooling for castings of plastic and metal, and other advances in materials and processes have added to the developer's options for rapidly producing parts as the design and testing is completed.

Our global economy has forced manufacturers to shorten the time between customer demand and delivery, improve first-time quality, and produce at a cost that is truly competitive in the world marketplace. Total real-time cooperation between all players and disciplines must continue to accelerate at a rapid pace. This will demand new tools and processes to support our development of new and better products.

ACKNOWLEDGMENTS

The author wishes to thank Technicomp, Inc., for allowing us to introduce part of their QFD system in this handbook, because we consider it one of the important tools that should be in the industrial engineer's toolbox.

FURTHER READING

Armstrong Mold Company, 6910 Manlius Road, East Syracuse, NY 13057. (brochure)
Dayton Rogers Mfg. Company, 2824 13th Avenue South, Minneapolis, MN 55407. (booklet)
Microphoto, Inc., 6130 Casmere, Detroit, MI 48212. (marketing literature)
TECHNICOMP, Inc., 1111 Chester Avenue, Cleveland, OH 44114-3516. (booklet)

Uni-Cast, Inc., 45 East Hollis Street, Nashua, NH 03060. (specifications)
Walker, Jack M., *Handbook of Manufacturing Engineering,* Marcel Dekker, New York, 1996. (handbook)

BIOGRAPHY

Jack M. Walker, who is presently active as a consultant in design and production areas, has held the following positions:

- Director of Factory Operations (Ret.) for McDonnell Douglas high-rate missile programs, involved in all elements of production and production support
- Resident manager of European coproduction programs, working with Swiss and Dutch industry
- Branch manager of Production Design Engineering—also wrote *Production Design* manual and *Introduction to Composites*
- Editor of *Handbook of Manufacturing Engineering* for Marcel Dekker, New York—wrote several chapters in handbook
- Senior member of SME, Professional Member of AIAA, and member of ASM
- Industry member of University of Florida Engineering Advisory Council
- Executive Director of Brevard County Manufacturer's Association.

CHAPTER 13.2

DESIGN FOR MANUFACTURE AND ASSEMBLY

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This chapter describes the process of analyzing product designs in order to identify design changes that will improve assembly and manufacturing efficiency. The process consists of three main steps: (1) design for assembly (DFA), (2) selection of materials and processes, and (3) design for individual part manufacture (DFM). The process of applying these three analysis steps is referred to as *design for manufacture and assembly* (DFMA). Case studies are presented in the chapter to show that DFMA can produce dramatic cost reductions, coupled with substantial quality improvements.

INTRODUCTION

Changes in the Product Development Process

A complete change has taken place in the process of product development over the past decade. The seeds of this change were planted in the early 1980s with two separate developments which were to come together over a period of several years. The first of these seeds was a redefinition of the expected outcome of the activity of design for manufacture. The redefinition arose in major part from a National Science Foundation–funded research program at the University of Massachusetts (UMASS) [1]. This work formed the basis for a Design for Manufacture Research Center at the University of Rhode Island (URI) which has been in existence since 1985. Research at URI over the past decade [2–5] has changed the process, which has become known as DFMA™ (Design for Manufacture and Assembly)*, from tables and look-up charts to interactive computer software used throughout the world [6]. The process of DFMA is now well established in industrial product development [7–10].

The second change started in the early 1980s with the recognition by a few U.S. corporations that product design was simply too important to be entrusted to design engineers working in isolation. This lead to the establishment of new procedures for product development in which product performance and the required manufacturing procedures for the product are considered together from the earliest concept stages of a new design. This process was gradually adopted in the development of consumer products, where the title of *simultaneous engi-*

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* DFMA is a trademark of Boothroyd Dewhurst, Inc.

neering or *concurrent engineering* was usually given to it. The main ingredient of simultaneous or concurrent engineering is the establishment of cross-functional product development teams which encompass the knowledge and expertise necessary to ensure that all of the requirements of a new product are addressed. These requirements are usually defined to be that (1) the product should meet customer performance requirements and (2) should be efficient to manufacture in order to meet both cost and quality goals. The core product development team then comprises personnel from the marketing and the design, industrial, and manufacturing engineering departments. By the end of the 1980s, simultaneous engineering had become synonymous with design for manufacture and assembly, and had become widely adopted across U.S. industry [11].

Simultaneous engineering is now the accepted method of product development. It has been stated that manufacturers of discrete goods who do not practice simultaneous engineering will be unlikely to survive in today's competitive global markets. This widespread adoption of simultaneous engineering has increased the need in product development for formal methods of design for manufacture so that manufacturing efficiency measures can be obtained early in the design process. In this way the manufacturing representatives of the team become empowered in the decision-making process, and design choices are not based solely on performance comparisons that can be readily quantified with CAE tools. Also, when looking critically at the product development procedure with a view to changing to simultaneous engineering, many corporations had come to the realization that the bulk of the cost of a new product is locked in place from the earliest concept stage of design. Thus, if manufacturing cost is not assessed in these early stages, then it is often too late during detailed design execution to have any major effect on final product cost.

The Traditional Practice of Design for Manufacture

The term *design for manufacture* (DFM) is often applied to a process of using rules or guidelines to assist in the design of individual parts for efficient processing. In this form, DFM has been practiced for decades, and the rule sets have often been made available to designers through company-specific design manuals. An excellent recent example of this approach to DFM provides a compilation of rules for a large number of processes, provided by experts for each of the process methods [12]. Such rule sets are usually accompanied by information on material stock form availability; on the problems of achieving given tolerance and surface finish values; and information on the application of different coatings and surface treatments. Such information is clearly invaluable to design teams, who can be vulnerable to making very costly decisions about the design of individual parts if these are made without regard to the capabilities and limitations of the required manufacturing processes. However, if DFM rules are used as the main principles to guide a new design in the direction of manufacturing efficiency, then the result will usually be very unsatisfactory. The reason is that in order to achieve individual part manufacturing efficiency, the direction will invariably be one of individual part simplicity. This might take the form of sheet metal parts for which all of the bends can be produced simultaneously in a simple bending tool, or die castings that can be produced without the need for any mechanisms in the die, or powder metal parts that have the minimum number of different levels, and so on. Figure 13.2.1 is an illustration taken from a DFM industrial handbook [13] in which the manufacture and spot welding of two simple sheet metal parts is recommended instead of fabricating a more complex single cross-shaped part. Such advice is invariably bad. The end result of this guidance towards individual part simplicity will often be a product with an unnecessarily large number of individual functional parts, with a corresponding large number of interfaces between parts, and a large number of associated items for spacing, supporting, connecting, and securing those parts. At the assembly level (as opposed to the manufactured part level) the resulting product will often be very far from optimal with respect to total cost or reliability.

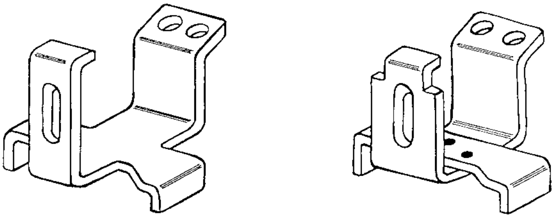


FIGURE 13.2.1 Single-part and two-part spot-welded designs. *(Reprinted with permission of Springer-Verlag.)*

The New Approach to Design for Manufacture and Assembly (DFMA)

The alternative approach to part-focused DFM is to concentrate initially on the structure of the product and try to reach team consensus on the design structure that is most likely to minimize cost when total parts manufacturing costs, assembly cost, and other cost sources are considered. The other cost sources may include the cost of reworking faulty products, and costs associated with manufacturing support such as purchasing, documentation, inventory, and so on. In addition, the likely costs of warranty service and support may be included if procedures are in place to quantify these costs at the early design stage. In this chapter we will focus our discussion on manufacturing and assembly cost reduction using the process of DFMA. We will also address the likely product quality benefits that arise from the application of the DFMA process.

Design for Manufacture and Assembly uses design for assembly (DFA) as the primary vehicle for decision making as to the structural form of the proposed product. The DFMA method can be represented by the flow chart shown in Fig. 13.2.2. The three upper blocks in Fig. 13.2.2 represent the main iteration loop in the process of identifying the optimal product structure. This iteration process stops when the team reaches some consensus as to the best product structure, coupled with the wisest choices of processes and associated materials to be used for the manufactured parts. In this iteration process DFA is the starting point and can be viewed as the driving activity. The process ends when the DFA analysis results are seen to represent a robust structure for the product which it is believed can be assembled efficiently. In Fig. 13.2.2 the activity of DFA is also referred to as *product simplification.* This is because DFA naturally guides the design team in the direction of part-count reduction. DFA challenges the product development team to reduce the time and cost required to assemble the product. Clearly, a powerful way to achieve this result is to reduce the number of parts that must be put together in the assembly process. This often leads to a review of the capabilities of the processes intended for use, to assess the possibilities for combining parts or bringing together required features into a single part. For the alternatives illustrated in Fig. 13.2.1, this would involve considering ways in which the cross-shaped blanks for the single-part design might be nested together, oriented at a 45° angle, in a row along strip or coil stock for stamping operations. Alternatively, for lower production quantities, the idea might be to array them overlapping as closely as possible on sheets to be made by turret press working. There may of course be other features that would be beneficial to incorporate into the part, and then the search might expand to other process and material combinations better suited to the new requirements. It is through such scenarios that *identification of materials and processes* becomes closely linked to DFA as shown in Fig. 13.2.2. Of course, the objective is control of total manufacturing cost and so it is important that the design team is able to obtain not only assembly cost estimates (through DFA) but also quick estimates of the cost of the manufactured parts to be used. This is the third part of the iteration process, referred to in Fig. 13.2.2 as *early cost estimating.* The need for early cost estimating procedures in product development cannot be overstressed. In many organizations the cost of proposed new parts cannot be obtained until detailed designs are available. This is invariably too late in the design process to consider radical changes in design; particularly if the changes require different process selections. It is for this reason that the writer and his colleagues have

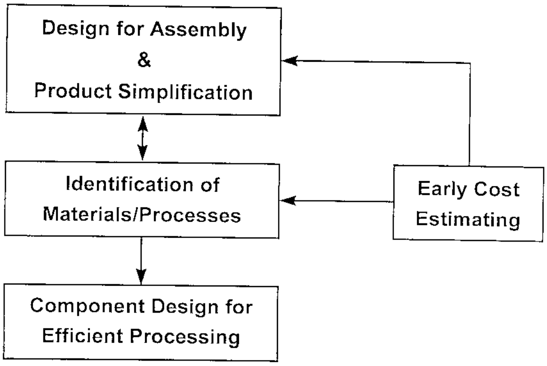


FIGURE 13.2.2 The Design for Manufacture and Assembly process.

been involved in developing economic models of processes which could be applied with only the limited amount of information available at the sketch stage of design [5].

The final stage in the DFMA process, as illustrated in Fig. 13.2.2, is *component design for efficient processing*. This is equivalent to the historical approach to DFM previously described. However, as part of the DFMA process, it is intended that this should occur only after the important decisions regarding product structure and process choices have been fully explored. In the case of the single cross-shaped sheet metal part shown in Fig. 13.2.1, this might involve in part: (1) ensuring that the most economical choice of alloy and gage thickness have been made; (2) adjusting the shape to facilitate closer nesting of the part, on the sheet or along the strip, to reduce scrap; (3) questioning the direction of the bend above the punched slot for easier forming; (4) checking that the tolerances on linear dimensions and angles are within standard press-working capabilities; and (5) increasing the profile radii of the bends if necessary so as not to exceed the ductility of the selected material.

DESIGN FOR ASSEMBLY

The Role of DFA in Product Simplification

Design for assembly is a systematic analysis procedure used during the early stages of product design for assessing assembly difficulties and for estimating assembly times or costs. Assembly difficulties which are identified during a DFA analysis are translated into appropriate time or cost penalties, and in this way a single measure (time or cost) represents the efficiency of the proposed design for the required assembly processes. The design team is then able to make adjustments to the design of parts or to the assembly sequence and get immediate feedback of the effect of such changes on assembly efficiency. However, DFA is also a vehicle for questioning the relationship between the parts in a design and for attempting to simplify the structure through combinations of parts or features, through alternative choices of securing methods, or through spatial relationship changes.

Dealing first with the spatial relationship of parts within a proposed product structure. Parts often exist in a design solely because of the chosen relative position of other items. For example, separate bracket supports may be required for two items that could be supported on the same bracket if they were moved into closer proximity. Alternatively, and much more commonly, parts may exist just as connectors between items that have been separated arbitrarily in the product structure. Such connectors may be used to transmit signals, electrical power, gasses, fluids, or forces for motions. For example, in a pressure recorder device illustrated in Fig. 13.2.3, previously analyzed by the writer and his colleagues [5], the tube assem-

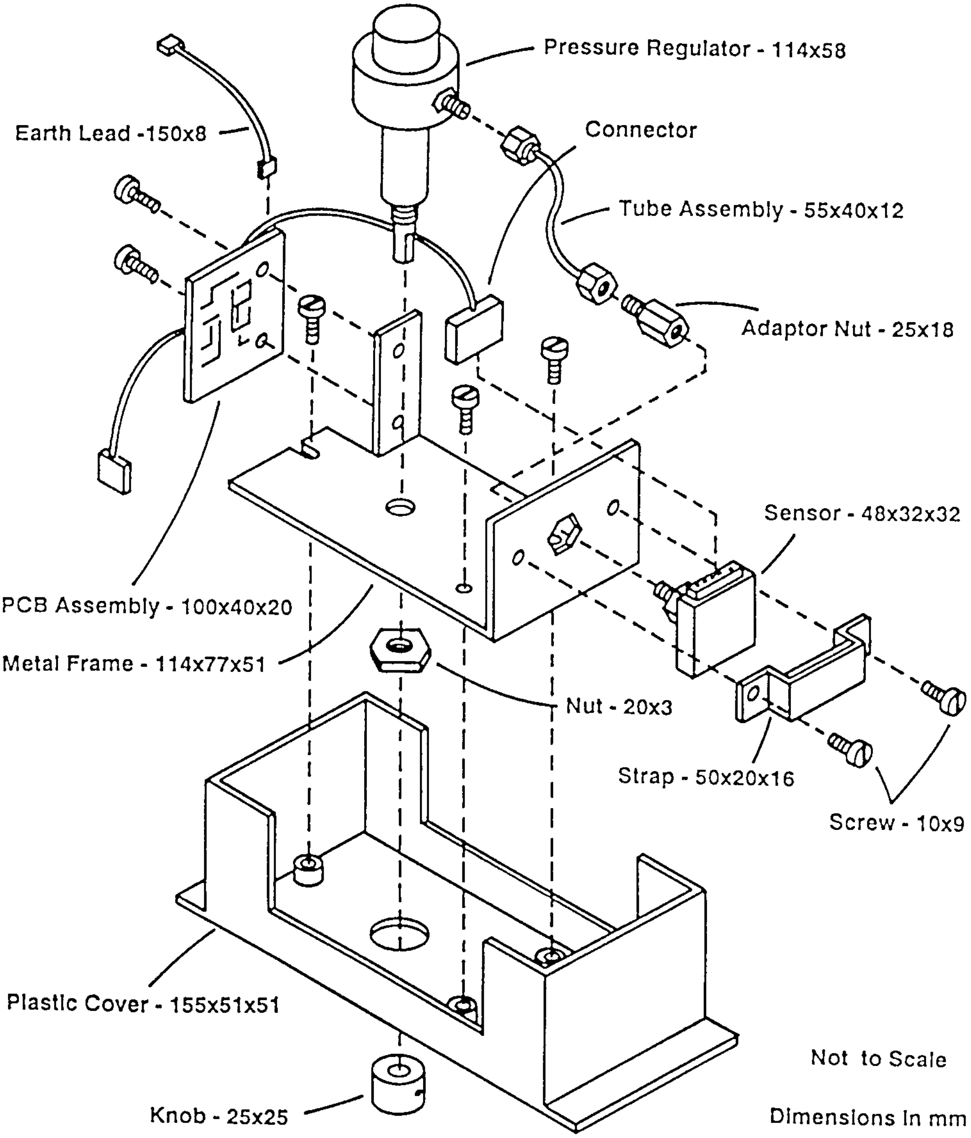

Pressure Regulator - 114x58
Earth Lead -150x8
Connector
Tube Assembly - 55x40x12
Adaptor Nut - 25x18
Sensor - 48x32x32
PCB Assembly - 100x40x20
Metal Frame - 114x77x51
Nut - 20x3
Strap - 50x20x16
Screw - 10x9
Plastic Cover - 155x51x51
Knob - 25x25
Not to Scale
Dimensions In mm

FIGURE 13.2.3 Existing design of a pressure recorder.

bly comprising five items (tube, two nuts, and two seals) is required simply because of the decision to mount the sensor onto the metal frame rather than to secure it directly to the pressure regulator. Also, the electrical lead labeled "connector" is needed because the sensor and the PCB assembly have been mounted onto opposite sides of the metal frame.

An important role of DFA is to assist in the determination of the most efficient fastening methods for necessary interfaces between separate items in a design. This is an important consideration since separate fasteners are often the most labor intensive items when considering mechanical assembly work. For the pressure recorder assembly in Fig. 13.2.3, for example, approximately 47 percent of the assembly time is spent on the insertion and tightening of separate screws and nuts. To reduce the assembly cost of dealing with separate fasteners, fastening methods which are an integral part of functional items should be considered. For plastic molded parts, well-designed snap fits of various types can often provide reliable high-quality fastening arrangements that are extremely efficient for product assembly [14,15]. Less commonly, sheet metal parts might be made from spring steel to incorporate integral fastening features with savings in assembly cost more than sufficient to offset the increase in material cost. Alternatively, metal parts may be made with projections for riveting or forming of permanent joints, or they may be press-fitted together or contain threads for screw fastening.

It is worth paying specific attention to screw fastening, since this is the most widely used method of securing in mechanical assemblies—and unfortunately, it is also the most inefficient method. Table 13.2.1 gives industry-average DFA time estimates [6] for assembling a cover part to a base using a variety of alternative fastening arrangements. These times do not allow for any difficulties in the assembly steps except for hand starting of the screw fasteners as previously discussed. The cover is assumed to have a largest dimension equal to 100 mm and to be easy to align and self-locating. The snap-fit operation is assumed to be with rigid snap elements which are engaged simultaneously.

TABLE 13.2.1 Assembly of Cover by Alternative Methods

Method	Assembly time (sec.)
Snap fit	4.1
Press fit	7.3
Integral screw fastener	11.5
Rivet (4)	36.1
Machine screw (4)	40.5
Screw/washer/nut (4)	73.8

The time for press-fitting assumes the use of a small bench press with foot pedal or similar control. The time for integral screw fastening assumes the use of a jar-type cover, the need for careful starting of the cover thread, and approximately five turns for full tightening. The estimated time for riveting the cover assumes the use of four rivets which are hand-loaded into a power tool. Finally, for the installation of separate screws, screw thread engagement is assumed to be by hand, followed by tightening using a power tool. For the assembly method labeled "Machine screw (4)", four screws are assumed to be inserted into tapped holes in the base. The label "Screw/washer/nut (4)" refers to the fastening of the cover to a flange on the base with four screws inserted through the flange and one washer and nut fastened to each. Of course, the often-seen hardware combinations of two flat washers and one lock washer with every screw and nut have even higher assembly times.

It should also be mentioned that in addition to screw fastening being a relatively inefficient securing method, it is also recognized as being one of the least reliable methods. Screws can be cross-threaded, improperly torqued because of burrs or malformed threads, or loosened because of vibrations in service. Experiments conducted by Loctite Corporation show that transverse vibrations across a screw-fastened interface can rapidly unwind correctly torqued screws, even with any of the different types of standard lock washers [16]. In mechanical design it is preferable to consider screws or nuts as threaded "unfasteners" and to avoid their use in situations where joints do not need to be separated in service.

Avoiding separate connectors and separate fasteners wherever possible in a design does not ensure that the design has an optimum part count. To force the design team to consider every possibility for reducing the number of separate manufactured parts in an assembly, the BDI (Boothroyd Dewhurst, Inc.) DFA method [6] challenges each part according to three simple criteria. These are applied to each part in turn as the DFA analysis steps through the assembly sequence. The criteria are intended to be a catalyst to brainstorming of ideas for consolidation or elimination of parts. As each part is considered, the part is allowed to be defined as necessarily separate, if with respect to parts already assembled it: (1) must be made of different material for some fundamental performance-related reason, or must be isolated from parts for which the same material could be used; (2) must move in rigid-body fashion, involving rotation or translation not possible with flexure of an integrated part; and/or (3) must be separate for reasons of assembly (i.e., combination of the part with any others already assembled would make it impossible to position parts in their required locations).

If a part does not satisfy at least one of these three criteria, then it is considered to be a candidate for elimination. The design team is then expected to discuss possibilities and document ideas for eliminating the part from the design. In this way the results of a DFA analysis include a list of possibilities for product structure simplification in addition to the estimates of reduced assembly time and cost. The design team can then edit the DFA structure file to incorporate all or selected ideas from the list, update the part cost estimates, and develop a full cost estimate comparison for the revised design.

The DFA Time-Standard System

The DFA procedure utilizes a database of standard times for handling and insertion based on part size and symmetry, and on the securing method to be used. In addition, appropriate penalties are added for difficulties in handling or inserting items during assembly. The difficulties included in the DFA analysis procedure are those which incur a significant time penalty on the assembly processes. Avoidance of these difficulties thus represents the essence of good detail design for assembly. These can be presented as a set of rules, divided into the two categories of *part handling* and *part insertion,* as follows:

1. Part Handling:
   - Design parts so that they do not nest or interlock (tangle) together when in bulk.
   - Avoid flexible parts that do not maintain their shape under their own weight.
   - Avoid sharp edges or points on parts that are to be handled manually.
   - Make parts as symmetrical as possible.
   - If parts are not symmetrical, then ensure that the asymmetry is obvious.
2. Part Insertion:
   - If parts are not secured immediately on insertion, then ensure that mating surfaces hold the part in the correct position and orientation during subsequent operations.
   - Design mating parts with lips, leads, tapers, chamfers, and so on, so that alignment is easy.
   - Limit forces required for insertion of parts in manual assembly [17].
   - Choose clearances between parts so that jamming cannot occur during insertion. The required clearance for a given part can be established from the part thickness, hole or recess dimensions, and the coefficient of friction between the mating surfaces [6].
   - Select directions of insertion to minimize the need for reorienting the partially built assembly as assembly proceeds.
   - For manual assembly ensure that the assembler can see the mating surfaces or edges for ease of location of the parts to be inserted.
   - Ensure adequate access for the part, for the assembly worker's hand or fingers, or for the assembly tool if one is required.

The last three insertion rules are often satisfied by designing a product so that all parts are added vertically—so-called *Z-axis assembly.* However, it should be noted that Z-axis assembly is much more important for assembly automation than for manual assembly. With the former, vertical insertions can be performed by simpler, less expensive, and more reliable devices.

Assembly problems of the types just listed are identified during a DFA analysis. At the same time, parts are classified as only for fastening or connecting, or they are assessed, according to the three criteria, for independent existence. The results of the analysis are presented on a DFA worksheet, the rows of which provide information on each assembly step. Figure 13.2.4 shows the DFA worksheet for the pressure recorder assembly illustrated in Fig. 13.2.3. It can be seen that 24 steps are involved in final assembly of the pressure recorder, with an estimated total assembly time of 215 seconds. This is useful information to have at an early stage of assembly design. However, it is important to be able to interpret the data with respect to the goal of assembly efficiency.

At the detail level, we can review the times for the individual assembly steps and compare them to an ideal benchmark value. From the DFA time-standard database it can be determined that the average time per assembly step for bench assembly of items that present no assembly difficulties (all are easy to grasp, align, and insert with simple motions and small forces) is approximately 3 seconds. With this value in mind we can identify inefficient assembly steps on a DFA worksheet. For example, in Fig. 13.2.4, the first operation of placing the pressure regulator in the work fixture is an efficient one since it takes only 3.5 seconds. However, the next step of adding the metal frame to the pressure regulator is obviously inefficient, taking more than twice the benchmark time value. The problem with this item is the lack of any alignment features to fix the required angular orientation, and the need to hold down the item during the following operation. At the bottom of the worksheet, it can be seen that the process of inserting the three screws that secure the frame to the cover is the most inefficient of the assembly steps. The problem here is not only the difficulty of aligning the screws with the nonlocated frame and cover, but also the restricted access of the screws against the deep end walls of the cover and frame. If a separate cover and frame, secured by three screws, is the best design solution, then it would be an easy matter to put locating projections in the bottom of the injection-molded cover and move the screw locations adjacent to the side-wall cutouts for easier access. Attention to such details for ease of assembly is inexpensive at the early design phase, and DFA can be used to quantify the likely assembly cost benefits. However, as will be discussed later, the benefits of effi-

Item name	Number of items/ operations	Operation time, sec.	Minimum part count
Pressure regulator	1	3.5	1
Metal frame	1	7.4	1
Nut	1	9.1	0
Reorient	1	9.0	—
Sensor	1	8.4	1
Strap	1	8.3	0
Screw	2	19.6	0
Adapter nut	1	12.0	0
Tube assembly	1	7.0	0
Nut tighten	2	15.1	—
PCB assembly	1	12.1	1
Screw	2	19.6	0
Connector	1	6.9	0
Reorient	1	9.0	0
Knob	1	8.4	1
Set screw tighten	1	5.0	—
Plastic cover	1	8.4	0
Reorient	1	9.0	—
Screw	3	36.9	0
Totals:	24	214.7	5

FIGURE 13.2.4 DFA worksheet for the pressure recorder.

DESIGN FOR MANUFACTURE AND ASSEMBLY

cient, operator frustration-free assembly steps are likely to have the even more important benefit of improvements in product quality.

The DFA Index

The foregoing discussion, of the assembly of the frame and the cover, was preceded by the qualifier that detail improvements should be made if these separate items represent components of a "best design solution." A measure of the overall quality of the proposed design for assembly is obtained by using the numbers in the right-hand column of Fig. 13.2.4. These are obtained during DFA analysis by scoring only those items whose function is other than just fastening or connecting and which satisfy one of the three criteria for separate parts. The summation of these values then gives a total which is regarded as the theoretical minimum part count. For the pressure recorder this value is 5. The reverse of this value is that 19 of the 24 assembly steps are considered to be candidates for elimination. Ideas for actual elimination of these steps would have been documented during the DFA process. For example, it can be seen that the plastic cover (Fig. 13.2.3) was identified as an elimination candidate. This is because, with respect to the metal frame, it does not have to be made of a different material, does not have to move, and a combined cover and frame would not make it impossible to assemble the other necessary items in the product. Of course, this does not mean that a combined cover and frame part *must* be made from the same material as the metal frame. A more sensible choice in this case would be an engineering resin, so that an injection-molded structural cover can have features sufficient to support the pressure recorder, the PCB assembly, and the sensor; items supported by the metal frame in the initial design proposal.

The minimum part count can be used to determine a DFA Index [6], which includes not just the assessment of possible part-count redundancy but also the assembly difficulties in the design being analyzed. This is defined as

$$\text{DFA Index} = (N_m \times t_m)/t_a \times 100 \tag{13.2.1}$$

where N_m = theoretical minimum number of parts,
t_m = minimum assembly time per part,
t_a = estimated total assembly time.

For the pressure recorder, this gives

$$\text{DFA Index} = (5 \times 3)/214.7 \times 100$$
$$= 7.0$$

Since the ideal design *for assembly* would have a minimum number of items and no assembly difficulties, the DFA for such a design would be 100. The score of 7.0 for the pressure recorder, on a scale of 0 to 100, clearly identifies the need for substantial assembly efficiency improvements. If the required production volumes are sufficient to justify large custom tooling investments, then we could envision a design comprising only a structural cover, a pressure regulator, a sensor, a PCB, and a control knob. This would require a custom die-cast body on the pressure regulator, with an inlet boss and screw thread to match the screw connector on the sensor. The PCB could then connect directly to the sensor, and the structural cover could contain supports and snap features to fasten itself to matching steps or undercuts on the die-cast body of the pressure regulator and to secure the PCB. A push-on knob would then complete the assembly. Assuming these five items were easy to assemble, then this would comprise the ideal design for assembly. If it is not possible to justify manufacture of a custom pressure regulator, then the design must accommodate the nonmatching screw threads on the purchased pressure regulator and sensor. Also, the only method of securing the regulator to the structural cover would be with a separate nut as in the existing design. These compromises from the "ideal" design lead to a product structure, previously proposed by the writer and his colleagues [5], as shown in Fig.

13.2.5. It can be seen that the structural plastic cover has an extensive rib structure to provide the required stiffness. It also has three internal undercuts, labeled *board snaps,* into which the PCB will be snapped during connection to the sensor. A DFA worksheet for this new design is given in Fig. 13.2.6. Comparison of this with Fig. 13.2.4 shows that the estimated assembly time has decreased by 60 percent from the original design, and the DFA Index has increased from 7 to 19. Also the number of parts has been reduced dramatically from 18 to 7, and the number of separate assembly operations has been reduced from 6 to 3. The likely positive effects of this reduction of assembly operations, in addition to the decrease in assembly cost, will be discussed after considering other case studies.

DFA Case Studies

Two positive additional benefits of a DFA product redesign can be seen in a case study from Texas Instruments [18]. The original design of a gunsight mechanism is shown in Fig. 13.2.7, and the redesign after DFA analysis is illustrated in Fig. 13.2.8. In this case the original design was actually in production and yet the advantages of the redesign were so great that manufacture was changed to the new design. The part-count reduction is even more dramatic than

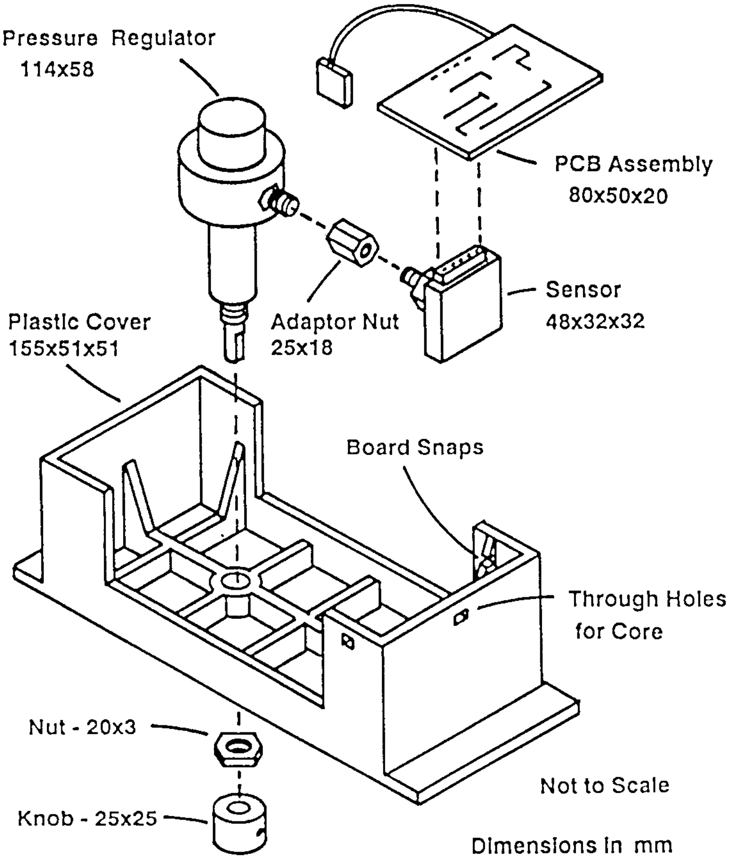

Pressure Regulator
114x58
PCB Assembly
80x50x20
Sensor
48x32x32
Plastic Cover
155x51x51
Adaptor Nut
25x18
Board Snaps
Through Holes
for Core
Nut - 20x3
Knob - 25x25
Not to Scale
Dimensions in mm

FIGURE 13.2.5 DFA redesign of the pressure recorder.

Item name	Number of items/ operations	Operation time, sec.	Minimum part count
Pressure regulator	1	3.5	1
Plastic cover	1	7.4	1
Nut	1	9.1	0
Knob	1	8.4	1
Set screw tighten	1	5.0	—
Reorient	1	9.0	—
Apply tape	1	12.0	—
Adapter nut	1	12.0	0
Sensor	1	9.9	1
PCB assembly	1	7.6	1
Totals:	10	83.9	5

FIGURE 13.2.6 DFA worksheet for the redesigned pressure recorder.

in the pressure recorder example previously cited. The effect of applying the minimum-parts criteria during analysis of the existing design can be considered for the case of the compression springs. When the first spring to be inserted into the carriage subassembly is considered, it satisfies the need for a different material than exists in items already assembled. However, the next eight springs do not have to be made from different material than already present (in the first spring), do not have to move in rigid-body fashion, and do not have to be separate for assembly purposes. This may lead the design team to consider a single custom spring formed from spring steel wire or stamped and formed from spring steel sheet; or to consider ways of simply eliminating one or more of the standard compression springs. It can be seen in Fig. 13.2.8 that the latter approach prevailed, with a resulting design containing only two springs.

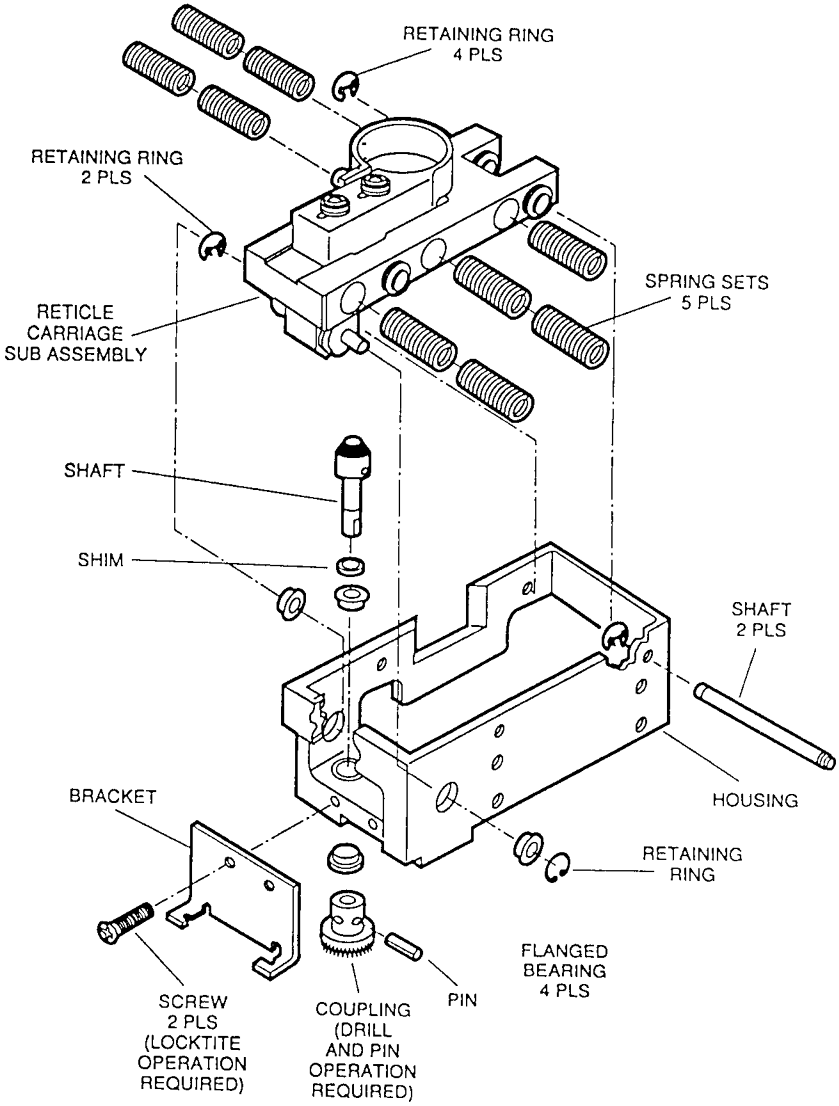
Table 13.2.2 show the benefits of the redesigned gunsight mechanism [18]. The reduction of assembly time by 84.7 percent represents the intended achievement of the DFA analysis. However, it can be seen that a much larger saving has been obtained in part manufacturing time—8.98 hr reduction, compared to 1.82 hr saved in assembly time. This result is typical of designs with greatly simplified structures resulting from DFA application. While a few parts may often become individually more expensive, this is usually more than offset by the savings from elimination of other items.

At this point it is worth mentioning that the savings from elimination of items in a simplified design go far beyond the savings from elimination of materials and manufacturing processes. Eliminated parts also remove associated costs for purchasing, inventory, quality control, documentation, production control, and scheduling. Savings in these overhead functions can often outweigh the reduction in direct manufacturing and assembly costs.

Table 13.2.3 shows the benefits of DFA implementation obtained from 94 case studies published in the literature [19]. The numbers in the second column of the table refer to the total number of references to each particular benefit in the 94 cases. Perhaps the most important indirect benefit listed in the table is the reduction of assembly defects. Unfortunately this was measured and reported in only 3 of the 94 case studies. However, one of these cases produced some profound results on the effect of assembly times and efficiency on defect rates, and this will be discussed in the next section.

ASSEMBLY QUALITY

Design for assembly has been used by Motorola Inc. since the mid-1980s to simplify products and reduce assembly costs. In 1991 they reported the results of a DFA redesign of the motor vehicle adapter for their family of two-way professional handheld radios [20]. Their bench-


RETAINING RING
4 PLS
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5 PLS
RETICLE
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SUB ASSEMBLY
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2 PLS
HOUSING
BRACKET
RETAINING
RING
FLANGED
BEARING
4 PLS
SCREW
2 PLS
(LOCKTITE
OPERATION
REQUIRED)
COUPLING
(DRILL
AND PIN
OPERATION
REQUIRED)
PIN

FIGURE 13.2.7 Original design of a gunsight mechanism. (*Reprinted with permission from* Industry Week.)

marking of competitors' electronic products indicated a best-in-class DFA Index value, as given by Eq. (13.2.1), of 50 percent, and they evaluated many different concepts to reach that goal. The final design had 78 percent fewer parts than their previous vehicle adapter and an 87 percent reduction in assembly time. They also measured the assembly defect rates of the new design in production and compared the results to defect rates for the old design. The result was a reduction of 80 percent in defect rates per part, roughly equivalent to the percentage part count reduction. However, combining the 78 percent reduction in part count with an 80 percent reduction in assembly defects per part gives a startling 95.6 percent reduction in assembly defects per product. Encouraged by this result, the Motorola engineers sur-

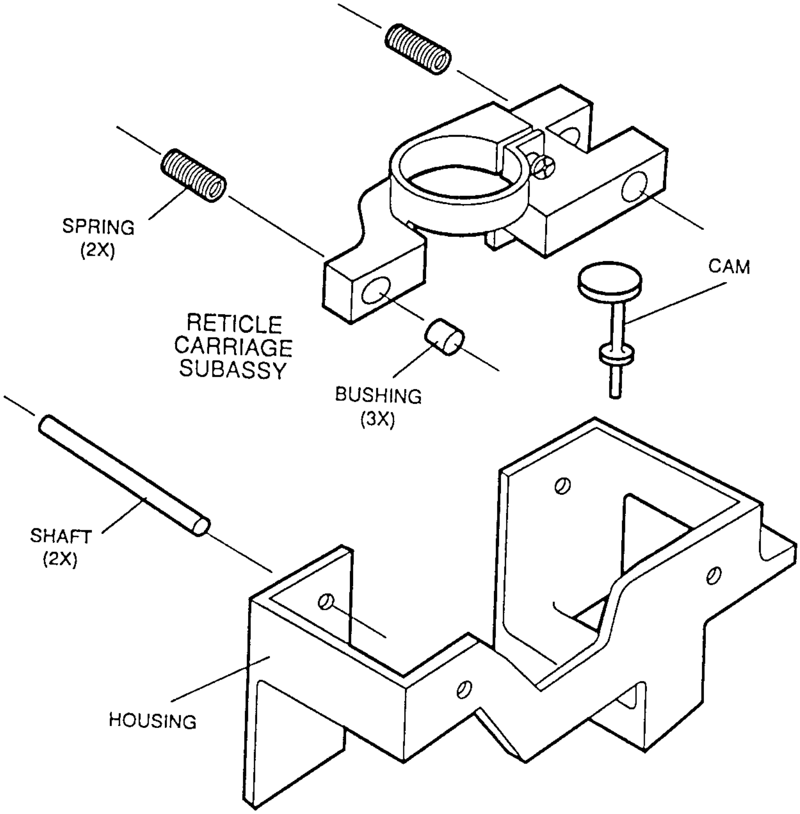

FIGURE 13.2.8 DFA redesign of a gunsight mechanism. (*Reprinted with permission from* Industry Week.)

veyed a number of products which had been analyzed using DFA and produced a correlation between assembly defects per part and the DFA Index as shown in Fig. 13.2.9. This clearly shows a strong relationship between assembly quality and the DFA Index values.

This Motorola data was subsequently analyzed independently by other researchers [21] to produce an even more powerful relationship for use in early design evaluation. These researchers postulated that since assembly time can be related to increasing difficulty of assembly operations, then the probability of an assembly error may also be a function of assembly operation time. In the study it was reported that 50 combinations of defect rates to assembly characteristics were tested for meaningful correlation. Of these, the variation of average assembly defect rate per operation with average DFA time estimate per operation showed the strongest linear correlation, with correlation coefficient $r = 0.94$. The actual data is shown illustrated in Fig. 13.2.10. The equation of the regression line is given by

$$D_i = 0.0001\,(t_i - 3.3) \tag{13.2.2}$$

where D_i = average probability of assembly defect per operation
t_i = average assembly time per operation

As mentioned earlier, the average assembly time for small parts that present no assembly difficulties is approximately 3 seconds from the DFA time-standard database. Thus Eq. (13.2.2) can be interpreted as an estimated assembly defect rate of 0.0001, or 1 in 10,000, for every second of extra time associated with difficulties of assembly.

TABLE 13.2.2 Benefits of DFA Redesign of a Gunsight Mechanism

Attribute	Original design	Redesign	Improvement (%)
Assembly time (hr)	2.15	0.33	85
Number of different parts	24	8	67
Total number of parts	47	12	75
Total number of operations	58	13	78
Part manufacturing time (hr)	12.63	3.65	71
Weight (lb)	0.48	0.26	46

For a product requiring *n* assembly operations, the probability of one or more assembly defects is therefore

$$D_a = 1 - [1 - 0.0001\,(t_i - 3.3)]^n \tag{13.2.3}$$

This relationship can be applied very easily in the early stages of design to compare the possible assembly reject rates of alternative design ideas. This can provide powerful directional guidance for product quality improvements, since it is becoming widely accepted that faulty assembly steps are more often the reason for production defects than part variability [22].

For the pressure recorder example, the existing design has an average DFA assembly time per operation of 8.95 seconds for a total of 34 operations; see Fig. 13.2.4. Applying Eq. (13.2.3) then gives an estimated probability of a defective assembly as 0.13, or 13 per 1000. For the redesigned pressure recorder, the number of operations is 10 with an average time of 8.39 seconds, and the likely number of defective assemblies is predicted to be 5 per 1000, a likely quality improvement of 60 percent from the original design. This could be improved further by considering detail design improvements to reduce the average operation time from the still-high value of 8.39 seconds. This might involve adding features to the plastic cover to make it self-locating when placed on the pressure regulator, using a counter-bored nut for easy alignment, and using an adhesive applicator for thread sealing/locking instead of the tape application. The effect of such changes on the likely defect rate could be tested by making appropriate changes in DFA and reapplying Eq. (13.2.3).

TABLE 13.2.3 DFA Results from 94 Published Case Studies

Category	No. of cases	Average reduction (%)
Part count	80	53
Assembly time	49	61
Product cost	21	50
Assembly cost	17	45
Assembly operations	20	53
Separate fasteners	15	67
Labor costs	8	42
Manufacturing cycle	6	58
Weight	6	31
Assembly tools	5	69
Part cost	4	45
Unique parts	4	59
Material cost	4	32
Manufacturing process steps	3	45
No. of suppliers	4	51
Assembly defects	3	68
Cost savings per year	6	$1,283,000

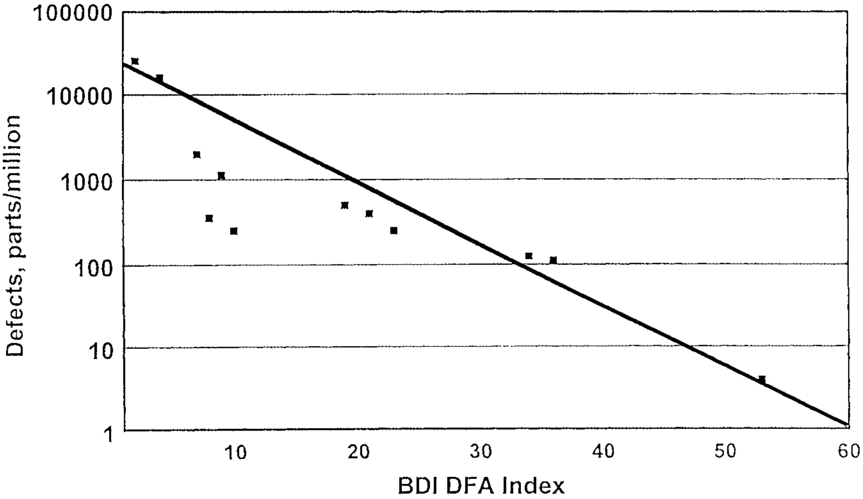

FIGURE 13.2.9 Relationship between assembly defects and the DFA index.

Finally, it should be noted that the previous calculations can readily be extended to include assembly defects due to part variability [21]. A recent version of DFA software [6] contains such calculations together with confidence intervals of the predicted quality levels.

CHOICE OF MATERIALS AND PROCESSES

It has long been recognized that product designers often only consider a very few of the wide range of material and process combinations that are available for product design [23]. Much of the reason for this stems from the personal responsibility for lifetime successful performance of the product, that rests with the design team. This, coupled with an often too-short design time,

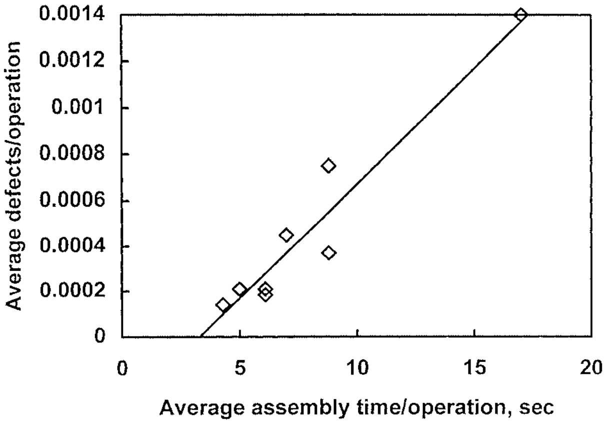

FIGURE 13.2.10 Relationship between assembly defects and average assembly time per operation.

leads designers to choose the processes with which they are comfortable and familiar. Only if a particular design requirement cannot be satisfied by these familiar processes will the design team be forced to explore the wider range of process possibilities. In this way design is too often the art of the possible, and lower-cost manufacturing solutions are overlooked.

A system that would guide a product design team to make wise choices of material and process combinations, at the earliest stages of design, would be of tremendous value. Unfortunately, little progress has been made in this important area. Some work was carried out in the early 1980s in development of a system called MAPS, for *material and process selection* [24]. This was a FORTRAN-based mainframe program for selection of primary shape forming processes based on part size, geometry classification, and performance requirements. The system had two major limitations. First, it did not allow for the stock form availability of materials. For example, an input that the desired part should be circular and prismatic in shape would be likely to produce wire or bar drawing as a possible process. Second, it did not allow for the possibility of a sequence of processes to satisfy the desired requirements. Thus secondary machining operations could satisfy the tolerance or surface finish requirements not possible by casting, or coatings could be used satisfactorily on a material excluded because of corrosion resistance requirements, and so on. Later attempts to overcome these limitations were made with a PC-based system using a commercial relational database [25]. This system, called CAMPS (*computer-aided material and process selection*), allowed what-if games to be played with shape and performance requirements with immediate feedback on process and material possibilities. However, linking of the system with automatic process sequence generation was never achieved satisfactorily.

Experience with the CAMPS system has led the writer to the belief that specifying both material performance and geometric shape requirements for such a system is too constraining. Often at the end of this process CAMPS would only suggest a very few, often obvious, candidates. A preferable approach, in the writer's view, if a wider range of alternative possibilities is sought, is to concentrate first on just material performance requirements. This approach can often produce surprising material candidates, and the identification of associated processes will lead to geometric shapes that are different from what might initially have been chosen. Selection of material can be based on fundamental material properties such as yield stress, fracture toughness, Young's modulus, and so on. For example, assume that wall stiffness is important in the design of a part. The design team would then know that the value of Young's modulus will be important. However, the minimum acceptable value of Young's modulus cannot be determined until the cross-sectional area or wall thickness of the loaded region has been defined. This in turn may depend upon the material cost, acceptable weight, or capabilities of the selected process. One way to proceed with this problem is to utilize derived material properties that more closely match the design requirement. If the part wall is to be subjected to bending movements and low weight is a design requirement, then a defined parameter which represents bending stiffness per weight would be useful for selection purposes. Such defined parameters have been used by Dieter [26] and Ashby [27] for material selection purposes. Reference to the book by Ashby can be made to verify that the defined property for bending stiffness per weight is given by

$$P_1 = E^{1/3}/\rho \tag{13.2.4}$$

where E = Young's modulus
ρ = material density

Materials with a high value of P_1 can then be investigated further with regard to shape possibilities and comparative costs. However, if minimum material cost is really the more important consideration, then the defined property for bending stiffness per unit cost simply becomes

$$P_2 = E^{1/3}/(\rho C_m) \tag{13.2.5}$$

where C_m = material cost per unit weight

Materials with a high value of P_2 could then be compared with respect to possible shapes and weights.

Recent work by the writer has been concerned with transforming the important derived parameters in mechanical design, such as the two just given, onto common 0 to 100 scales [28]. This allows for easy concept design selection without regard to the units to be used for subsequent design calculations.

Irrespective of the material selection criteria, cost is invariably important, and it cannot be obtained without considering both material cost and the effect of material selection on processing cost. For this reason, early cost estimating is the key to design for manufacture. The ability to produce cost estimates must be available from the earliest sketch stages. Unfortunately, in many manufacturing organizations reliable cost information is not available until detailed drawings have been submitted to manufacturing or to vendors for formal quotes. This makes it impossible to consider the numerous alternatives that may be necessary to arrive at a low-cost solution. As an example of this process, the design of the structural cover for the pressure recorder will be considered.

The initial proposal for the cover design is illustrated in Fig. 13.2.5. The important decisions to be made with regard to the cost of the cover are the choice of the thermoplastic to be used and the detailed design of the features. For the former, it is a relatively easy matter to estimate the volume of material required for alternative polymers and thus find the lowest-cost material selections. However, if this is carried out independently of the effect on processing cost, then the least-cost solution is certainly not assured.

Assume that it is deemed necessary to have the main wall of the cover equivalent in stiffness to the 20-gage (0.91-mm) low carbon steel of the frame in the initial design; Fig. 13.2.3. From simple bending theory, this requires wall thickness values proportional to the cube root of the Young's modulus values of the alternative materials. Using this relationship, a low-cost polymer choice such as high-impact polystyrene would require a main wall thickness of 4.8 mm, while the more expensive engineering thermoplastic choice of glass-reinforced polycarbonate would require a wall thickness of only 3.3 mm. Thus the volume of a polycarbonate cover would be approximately 45 percent of the volume of a high-impact polystyrene one. However, since glass-filled polycarbonate is about four times as expensive per unit volume as high-impact polystyrene, based on just material cost polystyrene would be the obvious choice. However, if we consider the effect of the material choice on the injection molding cycle time, then the selection is not so obvious. Mold filling and mold opening and closing times are unlikely to be significantly different for the two material choices. However, the cooling time in the mold is proportional to the square of the part wall thickness and inversely proportional to the material thermal diffusivity [29, 30]. Using typical injection, mold, and ejection temperatures, and thermal diffusivity values for the two polymers, the cooling time in the mold for a polypropylene cover is likely to be 41 seconds compared to only 17 seconds for a glass-filled polycarbonate cover. It now becomes a question of machine rate to determine if the reduced cycle time will more than compensate for higher material cost. Such tradeoffs are common in material selection. Alternative material choices may affect material removal times, molding or forming cycle times, press sizes (and therefore press rates), die cost or die life, and so on. The most economical material choice, just like the most economical process choice, can only be determined through the use of process models which can provide accurate early cost assessments.

DETAIL DESIGN FOR MANUFACTURE

The details of each part design for ease of manufacture can have a substantial effect on the cost of individual items. A study at Rolls Royce in the United Kingdom [31] was carried out on parts that were currently being manufactured by the company, to identify any opportunities for cost reduction which had been missed. Of all of the avoidable costs that were identified in this study, 30 percent of them would have resulted from changes in the detail design of parts. Thus the final DFM checks on part design should not be forgotten, even though, as noted earlier, any detail design changes for easier manufacture should not unduly compromise an efficient structure for the product. This should be determined with the large picture of total manufacturing cost, assembly cost, and product quality in mind.

Taking the structural cover for the pressure recorder as a further example, the decision to include snap-fit features into the cover was justified for the resulting savings in assembly cost. However, the proposed design of these snap-fit features may possibly be improved. The concept of undercuts in the tapered ribs (gussets) as shown in Fig. 13.2.5 will require extra moving cores in the mold in order to prevent the part from becoming die-locked when it solidifies. With holes through the side walls corresponding to the undercuts, as shown in the figure, the cores can move outwards on slideways. The mold for the proposed design would require three of these slideway-mounted cores, so-called *core pulls.* The need for these core pulls could be avoided if the undercuts were separated from the underside board supports and if small holes were permissible in the face of the cover for core pins to protrude directly from the mold cavity to the undercut surfaces [15]. This small change could save an estimated 140 hours of mold-making time, with a corresponding mold cost reduction of approximately $6000 at current U.S. mold-making rates [32]. In addition, slots could be molded alongside the undercuts to produce cantilever elements. Through appropriate choice of cantilever length and width, this would allow much better control of assembly forces than would be possible with the side-wall distortion of the proposed design [15].

CONCLUDING COMMENTS

Effective design for manufacture must include recognition of the fact that assembly is part of the manufacturing process of a product. Even though assembly represents the final steps of manufacture there is great advantage to be gained by considering it first in design assessment. The result of this will be a drive toward simplicity of product structure with wide-ranging benefits in every activity from material or parts procurement to reliability and customer satisfaction.

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BIOGRAPHY

Peter Dewhurst is a professor of manufacturing and the director of the Design for Manufacture Research Center at the University of Rhode Island. He is also cofounder and a director of Boothroyd Dewhurst Inc., which develops and markets DFMA and related analysis software programs. He holds a B.Sc. degree with first-class honors, and M.Sc. and Ph.D. degrees in mechanical engineering. Prior to entering academia he had several years of industrial experience in production and product design.

Dr. Dewhurst has been the recipient of national and international awards, including the Sir Charles Reynold Fellowship, the Taylor Medal of the International College of Production Research (CIRP), and the National Medal of Technology.

CHAPTER 13.3

VALUE MANAGEMENT

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Value management is a function-based analytical methodology used to improve businesses by identifying opportunities to remove unnecessary costs from their products and services while assuring that quality, reliability, product performance, and other critical factors meet customer expectations. The value management methodology can be applied to products, manufacturing processes, administrative procedures, organizational studies, and construction projects. Studies may be performed on existing projects, projects in the process of being developed, or projects as they are being conceptualized. While many of the techniques used in value management can be applied by individuals, the most significant results are obtained through the application of the methodology by multidisciplined teams.

BACKGROUND

Value Management Overview

Value management (VM) is a function-based analytical methodology used to improve businesses by identifying opportunities to remove unnecessary costs from their products and services while assuring that quality, reliability, product performance, and other critical factors meet customer expectations.

There are two essential aspects to the application of value management: (1) the unique method of function analysis must be applied, and (2) the organized job plan steps must be followed in proper sequence. It is these factors that differentiate value management from other analytical or problem-solving methodologies.

Origin of Value Management

The process of VM is not new. It was developed during World War II, when shortages of strategic materials forced the adoption of alternative materials and methods. After the war, when industry adjusted back to peacetime standards, there was a tendency to return to the original concepts. However, at General Electric (GE), it was discovered that in a number of cases the new methods resulted in less expensive products that performed better than the original designs. The concept of an approach to improved cost-effectiveness and quality was the brainchild of Harry Erlicher, GE's vice president of purchasing and traffic. He assigned

Lawrence D. Miles, an electrical engineer, to the Purchasing Department to develop a methodology that would *cause* these changes to occur. Between 1947 and 1952, Larry Miles developed the basic techniques of what he originally called *value analysis.* Larry realized that analyzing *functions,* not parts or materials, was the key to improving product value and managing costs.

Since that time value management has spread throughout industry in North America and around the world. Today, value management is one of the most versatile and effective business improvement tools available to management. SAVE International, the Value Society, maintains standards for the application of value management, certifies value practitioners, and promotes the value methodology. SAVE International also maintains relationships with other value management societies in Canada, Japan, the European Economic Community, the United Kingdom, Australia, India, Brazil, Hungary, Russia, South Korea, and China.

Value Management and Cost Reduction

Because of significant cost savings that generally occur as a result of value management studies, VM is often associated with cost reduction. However, cost reduction and value management are distinctly different. Cost reduction activities are part-oriented. This usually means altering manufacturing methods, relaxing tolerances, thinning or changing material, and so on. Normally, this will produce savings without an alteration of the design concept. Value management is function-oriented and generally leads to new or refined concepts that perform needed functions more simply with higher quality and more economical manufacturing processes or construction techniques.

Simply stated, the objective of VM is to "take deliberate action to improve cost-effectiveness." In this definition the terms *deliberate action* and *cost-effectiveness* require further explanation to understand VM's direction and effort.

Deliberate action requires education and training, planning, organizational identity, and accountability. Cost-effectiveness not only includes cost reduction, but also encompasses the efforts to avoid cost, increase sales, and improve profits [1].

Products can be cost-reduced into extinction, as characteristics important to the customer may be lost in the cost-cutting process. The VM process protects against this occurrence and in most cases improves customer characteristics while reducing cost, thus enhancing the potential for improved profitability.

Concepts of Value

The objective of any VM study is to improve the value of whatever is being studied. Unfortunately, people have differing opinions about what affects the value of a product. It is also important to avoid confusing cost with value. Added material, labor, or overhead increases cost, but not necessarily value. If added cost does not improve the ability to perform the necessary functions, value is lessened.

The early VM definition for value was the relationship between function and cost. *Function* is defined as the intent or purpose of a system, product, or process operating within its normally prescribed manner. While cost is easy to measure, function is not. However, the characteristics of functions can be measured. The basic elements that allow us to measure the functions are performance and delivery characteristics.

Performance: Appropriate performance requires that the product or service have a predetermined level of quality, reliability, interchangeability, maintainability, producibility, and marketability.

Delivery: The customer requires acceptable delivery, usually at a specific place within a given time.

The relationship of these two elements and cost, as shown by the equation, is important to satisfy the customer and maximize value. From this relationship it is easy to see that value can be improved by either improving performance or delivery, or by reducing cost. While most VM studies have specific objectives such as quality improvement, cost reduction, or improved manufacturing throughput, making decisions based on the value relationships ensures that one element is not improved at the expense of another. Most VM studies result in the improvement of several elements of value simultaneously:

$$\text{Value} = \frac{\text{function}}{\text{cost}} = \frac{\text{performance} + \text{delivery}}{\text{cost}}$$

While the equation may imply that value is increased by minimizing cost, the ability to reliably accomplish the function, or how the product performs and the ability to deliver the product to the customer as needed, may be jeopardized at minimum cost. From this analysis of the value relationship the following definition for value has evolved:

> *Value: The most cost-effective way to reliably accomplish a function, which will meet the expectations of the customer.*

Value Management Applications

The value management methodology may be applied to products, manufacturing processes, administrative procedures, organizational studies, business planning and reengineering, and construction projects. This chapter will focus on the application of VM to manufacturing processes. VM can be applied to any aspect of the manufacturing process. Several examples are listed here.

- Component fabrications
- Assembly operations
- Casting, forging, molding operations
- Material handling or processing
- Tool setup and changes
- Tool room operations
- Work cells
- Just-in-time processing
- Facilities planning and layout

Phases of Value Management

Studies can be performed on existing projects, projects in the process of being developed, or projects as they are being conceptualized. The terms *value analysis* (VA), *value engineering* (VE), and *value control* (VC), while having specific definitions, refer to the same basic methodology, and through general usage have become synonymous. Today, *value management* has become generally accepted as a term encompassing all the others.

Value Analysis. Studies performed on existing projects are termed *value analysis.* In VA studies much is known about the current situation, and the VA team is taking a second look at the project to improve the situation. Generally some of the cost savings identified through VA studies are used to offset the cost of change. This term is also sometimes used to describe application of the methodology to a process or procedure.

Value Engineering. Studies performed on projects during the development phase are termed *value engineering.* In VE studies, some critical information is known about the project, and the VE team is analyzing the project before significant cost has been expended to set up the manufacturing for the project, thus significantly reducing the cost of change. VE applies not only to new designs but also to new manufacturing processes, procedures, and organizational studies.

Value Control. Value control studies are performed at the very onset of a project to help set cost and quality targets, develop the concept for the project, and to assure the project has long-term viability with the customer. Value control studies are often followed by VE studies as the design progresses to further optimize the design and proposed manufacturing process. Business or operational planning and business reengineering studies, which also use the VM techniques, are considered VC studies.

Regardless of the type of study, the VM basic approach and techniques are the same. The major differences between the various types of studies are how one prepares, and the information required, to successfully perform the study.

VALUE MANAGEMENT AND INDUSTRIAL ENGINEERING

A Changing World

Since value management originated over 50 years ago much has changed. Manufacturing labor was once the dominant business expense, and economy of scale and material flow were key elements in the drive to reduce labor's contribution to product cost. Direct labor and material cost management were primary elements in determining the success of a product and, therefore, the company [2].

Today, direct labor is often an insignificant part of a product cost. Economy of scale has given way to flexible manufacturing techniques where lot sizes and setup costs are no longer a major cost issue. Time-to-market, from innovation to market entry, has taken on more importance in business success than unit product cost. As a result, the focus of VM has moved from product cost to the production process. While reducing product cost is still an active VM target, reducing the cost of doing business and associated non-value-adding activities is taking on greater emphasis, because that is where the greatest potential for improvement exists. In addition, VM is now applied earlier in the life of the product, to define what the product should be and how to best manufacture it, as opposed to helping to refine the product or process.

Industrial Engineering Work System

Industrial engineering can be defined as the process by which an organization's tangible resources are allocated to best support the mission of the organization. In order to design efficient and effective systems of operations, it is necessary to understand the basic concept and characteristics of a work system. Any such system can be broken down into a conversion or processing of inputs into a set of outputs with different characteristics. Figure 13.3.1 displays the basic concept and characteristics of a work system [2].

A work system can be described as being composed of process inputs, a conversion process, and process outputs. The process inputs consist of personnel, methods, materials, equipment, facilities, and command, communications, and control (C3). The personnel input simply refers to personnel with appropriate skill types and levels (e.g., laborer, electrician, or welder). The term *method* as used here implies the set of detailed and systematic procedures employed to process a given product. Materials represent the required input of raw materials or components, whereas equipment represents all tangible devices, such as machines, tote boxes, cranes, and

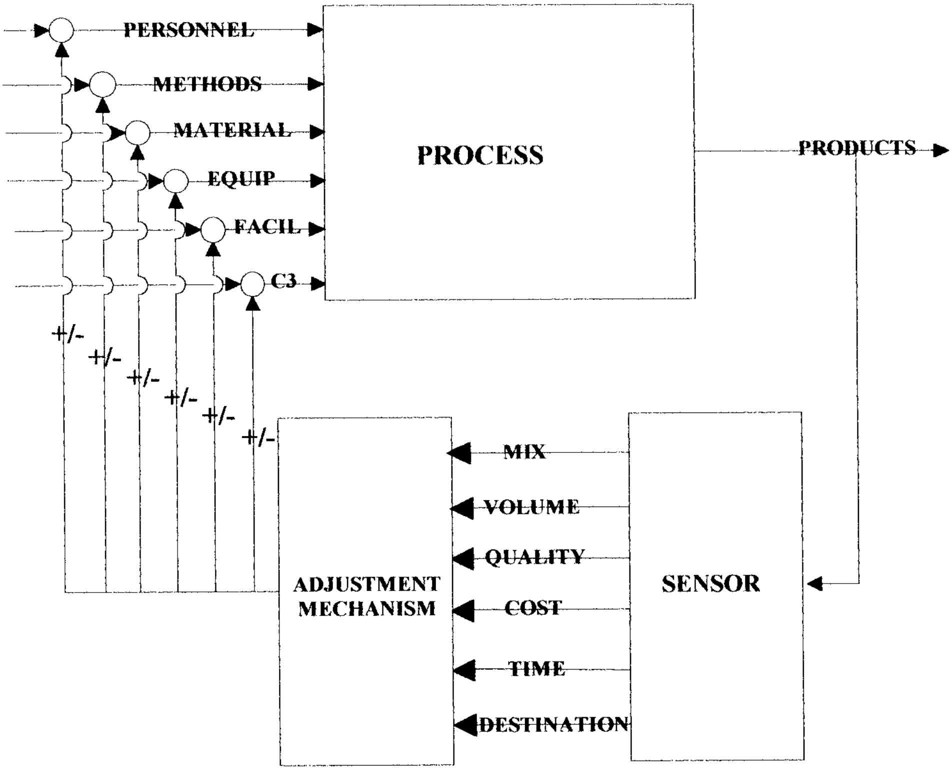


FIGURE 13.3.1 The work system.

conveyors, used in the processing of products. Facilities include physical structures used to house operations as well as utility distributions. Command, communications, and control represent the command structure and responsibilities of personnel, communication links between process inputs, and mechanisms for the proper control and application of input resources.

The outputs of the conversion process are products with measurable characteristics of mix, volume, quality, cost, time, and destination. Product mix refers to the set of distinct products produced, whereas volume is an extensive measure of the quantity or amount produced. The quality of a product refers to the degree of successful processing of a product. A modern and all-encompassing definition of product quality is the total loss imparted to the customer due to functional variation and harmful effects. This latter definition measures quality as the loss suffered by the consumer through product use with respect to (1) deviations of product performance from that intended by engineering design, and (2) deleterious effects that are unrelated to function but nonetheless impact the consumer. Product cost is the cost associated with manufacturing, utilities, and the like. Time and destination characteristics refer to the time, delivered to the required delivery destinations. Thus, time and destination characteristics are a measure of the adherence to the production schedule and the on-time delivery to the customer.

The set of input resources fully determines the achievable levels of process outputs. Therefore, the only way to effect improvement in the process outputs is to alter, in an appropriate manner, the process inputs. As a means to accomplish this, the process outputs must be measured or "sensed" and fed back to an adjustment mechanism that can correct the infusion of process inputs.

Value Management's Role in Processes Improvement

The value management process can be used as the methodology for the adjustment mechanism to analyze the process, the inputs, and the outputs to identify both minor changes (refinements) to the current process and where major process changes are warranted. In addition, the VM process can be used with product planning data to establish new processes.

VM PROCESS

Value Management Study

A VM study in an organization is the result of deliberate action being taken to improve a given situation [1]. It is not an ad hoc group that is trying to find ways to do something better. The project should be commissioned by the management team. Typically a member of the management team is the project sponsor or champion. Specific project scope and objectives are determined. A multidisciplinary team is assembled and a time budget for the study is established. A VM study typically requires four to six days for the core of the study. These days are generally contiguous, but are often split over two weeks. Preparation for the study generally requires two or three days. This time occurs during the month prior to the study. Following the study, the team verifies their facts and finalizes their alternatives before presenting their recommendations to the management team. The presentation to management is a decision meeting and culminates the VM study. Items are either accepted for implementation, rejected, or further analysis may be requested. Once an alternative has been accepted, it is implemented like any other change in the organization, and the VM team effort comes to a conclusion. Typically the total process requires approximately three months to go from study initiation to completion.

Job Plan

The job plan organizes the VM techniques and tools into a logical sequence to keep the team properly focused during the VM study and comprises seven major phases. Key to the success of the value management approach is following these steps in sequence and avoiding the temptation to try to reach a conclusion before the project has been thoroughly understood and analyzed. The majority of the information phase is accomplished prior to a value management study, and the reporting and implementing phases after the workshop. The steps of the job plan are discussed in the following sections.

Information. Gathering and reviewing the appropriate information prior to starting a project provides a team with a basic level of understanding. Depending on the type of study, the information required will vary slightly. Each type of study requires that customer needs and requirements are understood, specific projects and goals are defined, and current costs have been gathered and organized. The project scope should be clearly defined and understood by the team members so they can properly focus their efforts. Key VM tools applied during this phase include cost modeling, sequence flowcharts, Pareto analysis, and competitive benchmarking.

Function Analysis. Function analysis is the heart of the value management methodology. The ultimate objective of function analysis is to identify the functions that are not providing good value and need to be improved. There are three steps in function analysis. The first is simply defining the functions occurring in the project and categorizing the type of function. Next, the functions are organized into a function analysis system technique (FAST) diagram, which graphically illustrates how the functions relate to each other. The final step of function analysis is to identify which functions require improvements. This is accomplished through dimensioning of the FAST diagram. Typically this involves developing cost-function relationships, which is accomplished by assigning part of the process costs to the various functions. Through this process, the team can analyze which functions have excessive cost and do not provide good value to the customer. However, depending on the project and objectives of the study, the FAST diagram can be dimensioned with customer attitudes, quality data, responsibilities, or time.

Typically, three or four functions will stand out as requiring improvement, either from the cost-function relationships that were developed, or through the identification of the function(s) as a root cause of a quality, reliability, efficiency, or other, problem.

Speculation. In the speculation phase of the job plan, each function that was identified during the function analysis phase as needing improvement has its own creative session. During these creative sessions, any idea that can be associated with modifying that function is recorded so that it may be evaluated at a later time. Typically, this is done using brainstorming techniques and identifying numerous ideas for performing each function selected. Key to a successful creative session is to avoid the evaluation of the ideas during the creative process.

Several factors stimulate the need for creative processes. Every design is a compromise achieving only the best possible solution within a given time. New technology, new materials, new manufacturing processes, and new information are continuously being discovered and developed. Customer needs and desires are constantly changing. Thus creative opportunity exists and always will exist in every phase of industrial activity. The function analysis phase has provided the team with direction as to where new ideas need to be developed to improve the product or process. Now the team members must apply their creative ability.

In most industrial organizations it is difficult to be truly creative, as the work environment generally demands answers and not just ideas. People are constrained by not wanting to appear foolish by voicing an idea that may not be a potential solution, represents a totally different point of view on the problem, or challenges traditional thinking. Yet without searching for ideas, the best answer may never be uncovered.

During a creative session, the atmosphere must be open, positive, and receptive to the ideas being generated. Every idea needs to be verbalized and recorded. This may trigger yet another thought or idea in a teammate's mind, and maximizes the quantity of ideas generated. To assure that ideas have not been suppressed, judgment and evaluation are deferred during creativity. Not only must the team members refrain from judging ideas that are presented by others, but they must also refrain from judging their own ideas.

Even though the idea may not be initially considered a solution to the problem, it should not be excluded from the list. The objective is to develop a long list of *ideas, not answers.* By developing many ideas, we have the opportunity to select the idea(s) that best meet the criteria of the project.

Evaluation. The purpose of the evaluation phase is to systematically reduce the large number of ideas generated during the speculation phase to a number of concepts that appear promising in meeting the project's objectives. The evaluation process moves through the following steps.

1. Determine evaluative criteria.
2. Evaluate ideas.
    - Test with respect to criteria.
    - Identify advantages and disadvantages.
3. Rate ideas.
4. Conduct comparative analysis.

At the beginning of the evaluation phase, identify the criteria against which the ideas need to be evaluated. Then the ideas are discussed and evaluated with respect to this key evaluative criteria, and any additional advantages or disadvantages are noted. Based on this analysis the ideas are prioritized for development. When multiple alternatives exist for a specific project area, comparative analysis techniques are used to determine which of these mutually exclusive items would best meet the project objectives.

Development. Depending on the type of study being conducted, the development phase may be completed as part of the study or as follow-up to the study. The objective of this phase is to develop the concepts identified during the evaluation phase into specific proposals. Before the team starts to develop the proposals, it is often necessary to establish an action plan to organize and focus the team's efforts, as some of the work will be performed by individual team members and some by the team as a whole. With a good action plan in hand, the team can then develop and finalize each proposal.

Report. A value management study is concluded with a final written report and presentation to the management group regarding the team's recommendations on the project studied. The objective of the management presentation is to get a decision on the team's proposals so that any funding or action required to implement those proposals can be integrated into the company's plans. The team is not expected to implement the change; rather, the change is implemented as any other change would be implemented in the organization. Owing to the nature of their responsibilities, some team members may be part of the implementation effort.

Implement and Audit. While the implementation and auditing portions are not part of a value management study, they are crucial to the success of any value management activity. Because the objective of the study was to develop proposals that would improve on the cost-effectiveness, quality, and efficiency of the organization, nothing can be accomplished until the change has been implemented and the benefits received. To improve the effectiveness of a company's value management effort, it is beneficial to have a formal process to track the implementation status of the projects and audit the results. This will help to identify where there may be problems or delays in implementation, ensure the implementation is completed in a timely fashion, and verify the final benefits.

KEY VM TECHNIQUES

Information Phase Techniques

Value management projects are approved by the company's management staff. The rationale for selecting each project may vary slightly, but with each project management is looking to the VM team to provide specific recommendations that can improve the project. A clear understanding of what the project is and the conditions management hopes to see improved should come first.

Gather Background Information. In order for the teams to thoroughly understand the project and be prepared to conduct the study, some pertinent data need to be gathered. Listed here is some of the key information that needs to be gathered and reviewed prior to any study.

1. A sample of the items to be studied.
2. The bill of material listing all of the parts included in the project.
3. The assembly and part drawings.
4. The manufacturing routing for the items under study. These data should include detailed time and costs.

5. Marketing requirements, features, and annual or contract quantities.
6. Project specifications (material, manufacturing, purchasing, engineering).
7. Quality information (reject rate, scrap and rework costs, field problems, customer complaints, and the like).

Additional information beneficial for process and procedural studies:

8. A sequence flowchart that details the steps in the current process or procedure.
9. Any company policies and written procedures that define the present process or procedure.
10. Storage requirements for both raw material and finished goods inventory.
11. A layout showing the present flow of material and equipment locations of areas under study.
12. A list of the capital equipment currently used in the process.
13. Identification and quantification of other areas effected by the project.

Understand Customer Needs and Requirements. A key part of the project background information is to understand the project from the customer's point of view. If the product has been on the market for several years, it may be necessary to update the customer information. Are the customers' wants and needs the same as when the product was originally introduced? Have the customers' requirements changed? Are there new features the customer would like or must have? Are there any product concerns or problems? How does the competition's product differ from your product? These are all questions that should be asked prior to your value study. Many times the perceived wants and needs of your customers vary considerably from the customers' actual requirements.

Establish Objectives and Goals. The basic objectives and goals of the team are usually provided to the team by the management group or project initiator. After review of the project background, and based on the individual team members' knowledge of the project, objectives may be clarified and/or added to by the team. While many value studies traditionally focus on cost improvement, other objectives regarding quality, performance, and delivery are often important considerations. It is important that the team members understand not only what they are studying, but why, if they are to make recommendations that can best improve the product.

Determine Scope. To solve any problem, the parameters of the study must be clearly defined. While a large amount of documentation is gathered for a study, it is important to agree on what is included in the study and where the study stops—the interface points of the study—so the team can properly focus its efforts.

The scope of a design project is specified by listing the major components or subassemblies included in the study. The scope of a study of a hydraulic steering gear includes the *steering gear housing, rack, hydraulic valve assembly, tie rods, bellows, housing cover, guides, and bushings.* The scope does not include the *steering column coupling or attachments to the vehicle.* This provides the initial boundaries on what the team is studying and focuses its data gathering efforts.

A manufacturing process study is specified by first identifying the end points of the study and the major activities between those end points. And like the scope for the design study, key areas that are not included in the scope are identified to further clarify the project. In this case, the scope of a study of a hydraulic steering gear could be described as including the points *from the receipt of the casting through machining, final inspection, packaging, and shipping to the customer.* The scope does not include *casting the part or assembly into the turbine.*

It is important that the scope be used to focus the team's efforts on the specific project, but not limit the team. It is permissible for the team to expand the project scope if compelling data suggests this will be beneficial, but this should be verified with the project sponsor.

Understand Current Costs. *Cost* is one of the most misunderstood items in business today. The cost of the product under study may vary greatly, depending on whom you ask and what level of cost they are accustomed to using. Is the cost fully burdened? Does it include profit? Is it just material cost? Does the cost information reflect estimates, or are they based on quotes or other actual information?

Cost visibility techniques are used to organize the cost information, provide the team with a better understanding of the current cost situation, and identify which elements are driving the cost. First, the appropriate level of cost for the project is determined. Most organizations today use material, labor, and a variable portion of overhead for design studies. In manufacturing and administrative studies, the cost includes only labor and variable overhead. Material cost is considered a function of the design and is not included unless it relates to such things as scrap, excess required for manufacturing, and material consumed in testing. In procedural studies, it is important that you identify the true cost impact to the organization. It is not the cost of the direct steps of the procedure that is generally the issue; it is the secondary impacts that the procedure causes on the organization that creates the true cost. A procedure to approve capital funding at one company required an average of over 90 days to complete. The direct cost to process the capital funding requests was not very significant, but the productivity and effectiveness lost waiting for the funds to be approved cost the company millions of dollars annually. These types of cost impacts are critical to understand, model, and quantify for procedural studies.

By properly identifying, organizing, and documenting project cost, the team can focus on the product and process cost that can impact the study. The format for organizing the cost information varies slightly between design and process and procedural studies.

Product Design Studies. These studies use a cost visibility worksheet to organize the cost data. Figure 13.3.2 shows a typical product cost breakdown. The cost is organized to show the contribution of purchased parts, raw material, direct labor, and variable overhead by part or assembly.

Manufacturing Processes and Administrative Procedure Studies. These studies use a sequence flowchart to organize the cost information and to graphically detail the process or procedure as it currently exists. This chart shows the sequence of events and groups involved in the process or procedure, the time and cost of each event, the elapsed time between the start of one event and the start of the next, and any miscellaneous cost. This document provides the team with easy-to-understand current information regarding the study project. An example of a sequence flowchart is shown in Fig. 13.3.3.

To establish a base for determining cost improvements, the annualized cost of the study item is calculated by multiplying the unit cost by the number of pieces produced per year, or the process cost by the number of times the process is repeated annually. The annualized cost is used to determine annualized savings:

$$\text{Annual project cost (current)} - \text{annual project cost (proposed)}$$
$$= \text{gross annual savings} - \text{cost of change} = \text{net first-year savings}$$

In most studies, projects that show a payback in less than one year are easily accepted by management for implementation.

Function Analysis Techniques

Function analysis techniques are used in defining, analyzing, and understanding the functions of a project, how the functions relate to one another, and which functions require attention if the value of a project is to be improved.

Definition of Functions. All functions are defined by two words—an active verb and a measurable noun. To state what something does in two words is sometimes difficult, but it helps to simplify terminology, improve communications, and create better understanding. When choosing the words that define function, make them broad and generic. Words that predetermine the way the function is to be performed should be avoided.

Project: Item: Steering Gear - Hydraulic Assist

Material Cost: $60.44 Labor Cost: $39.71 Variable Overhead: $34.12

Unit Cost: $134.27 Annual Volume: 225,000 Annual Cost: $30,210,750

Identification Number		Quantity	Purchase Parts $	Raw Material $	Direct Labor $	Variable OH $	Total $
1732458	Valve Assembly	1	$3.95	$5.22	$7.98	$6.38	$23.53
2257483	Housing Assembly	1	$14.66		$11.78	$11.78	$38.22
7745356	Tie Rod Assembly	2	$15.22	$6.01	$3.48	$2.78	$27.49
1733339	Tube Assembly	1		$2.26	$2.78	$2.22	$7.26
9547345	Rack	1		$2.59	$6.77	$5.42	$14.78
1233445	Bellows	1	$1.90				$1.90
1436459	Rod Bushing	4	$3.21				$3.21
1000576	Rack Guide	1	$3.59				$3.59
1743855	Housing Cover	1		$0.29	$0.50	$0.40	$1.19
	Final Assembly				$4.90	$3.92	$8.82
	Packaging		$0.35		$0.27	$0.22	$0.84
	Scrap		$0.89	$0.30	$1.25	$1.00	$3.44
	TOTAL:		$43.77	$16.67	$39.71	$34.12	$134.27

FIGURE 13.3.2 Cost visibility worksheet.

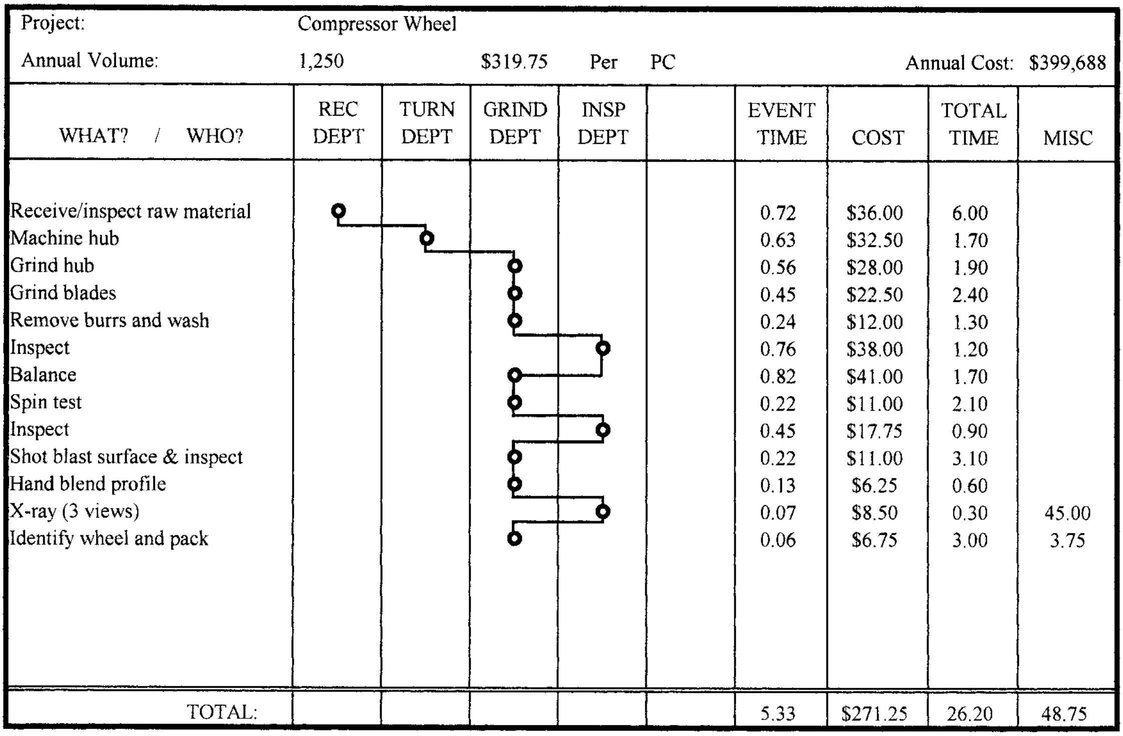
For a design study, electric motors produce torque, lightbulbs generate light, a steering gear transmits force, and calrods produce heat. In manufacturing process studies, a machining or casting process is designed to shape material, a material-handling procedure is designed to deliver material, and an inspection process is to verify product. In administrative procedure studies, a payroll system is designed to distribute payroll, an inspection report procedure is designed to identify status, and a project approval procedure is designed to authorize change. Simple statements such as these ensure clarity of thought and enhance project understanding.

The selection of a noun is also important. Try to select a noun that can be expressed as a measurable parameter. For instance, a shaft "transmits torque," not "rotate pulley." We can quantify torque and answer the question, "How much torque?"

There are three major types of functions within the scope of a study item—basic, secondary, and higher order. The *basic function* is the specific work that a product, process, or procedure is designed to accomplish. *Secondary functions* are the other functions that the device performs and are subordinate to the basic function. They support the basic function and allow the product, process, or procedure to work and sell. Secondary functions may be categorized as either required, aesthetic, or unwanted. Required secondary functions are necessary to allow the basic function to happen or happen better. Aesthetic secondary functions improve the appearance of the product and make it more desirable to the customer. Unwanted secondary functions are generally undesirable by-products of either the basic or other secondary functions and often require additional cost to minimize their impact. *Higher-order function* identifies the purpose for the product or process and explains why the basic function is performed.

As examples of the various categories of functions, consider:

- *An overhead projector:* Its basic function is to project images. In addition, the overhead projector has many required secondary functions, such as convert energy, generate light, focus



Project: Compressor Wheel

Annual Volume: 1,250 $319.75 Per PC Annual Cost: $399,688

WHAT? / WHO?	REC DEPT	TURN DEPT	GRIND DEPT	INSP DEPT		EVENT TIME	COST	TOTAL TIME	MISC
Receive/inspect raw material	○					0.72	$36.00	6.00	
Machine hub		○				0.63	$32.50	1.70	
Grind hub			○			0.56	$28.00	1.90	
Grind blades			○			0.45	$22.50	2.40	
Remove burrs and wash			○			0.24	$12.00	1.30	
Inspect				○		0.76	$38.00	1.20	
Balance			○			0.82	$41.00	1.70	
Spin test			○			0.22	$11.00	2.10	
Inspect				○		0.45	$17.75	0.90	
Shot blast surface & inspect			○			0.22	$11.00	3.10	
Hand blend profile			○			0.13	$6.25	0.60	
X-ray (3 views)				○		0.07	$8.50	0.30	45.00
Identify wheel and pack			○			0.06	$6.75	3.00	3.75
TOTAL:						5.33	$271.25	26.20	48.75

FIGURE 13.3.3 Sequence flowchart.

image, enlarge image, receive current, transmit current, and support weight. Unwanted functions such as generate heat and generate noise and the aesthetic function of enhance décor also exist. The higher-order function of the projector may be to aid communication.

- *A manufacturing process:* Its basic function is to produce product. In addition, the manufacturing process has many secondary functions, such as generate shape, move material, attach components, inspect product, store materials, protect product, set up equipment, and smooth surface. Generate scrap is an unwanted function that plagues most manufacturing processes. Aesthetic functions are generally not found in manufacturing processes. The higher-order function of the manufacturing process may be to satisfy order.
- *A hiring procedure:* The basic function is to fill vacancy. In addition, the hiring procedure has many secondary functions, such as create announcement, interview candidates, prepare requisition, conduct orientation, evaluate application, and select candidate. While administrative procedures may have unwanted functions, aesthetic functions are rare. The higher-order function of the hiring procedure may be to staff project.

FAST Diagram. The function analysis system technique diagram is a powerful value management technique that (1) shows the specific relationships of all functions with respect to each other, (2) tests the validity of the functions under study, (3) helps identify mission functions, (4) broadens the knowledge of all team members with respect to the project, and (5) significantly improves communication, as it represents team consensus of the project scope. At first glance, a FAST diagram appears to be similar to a flowchart. However, the basic difference between FAST diagramming and flowcharts is that FAST is function-oriented and not time-oriented. Figure 13.3.4 shows the basic ground rules for developing a FAST diagram.

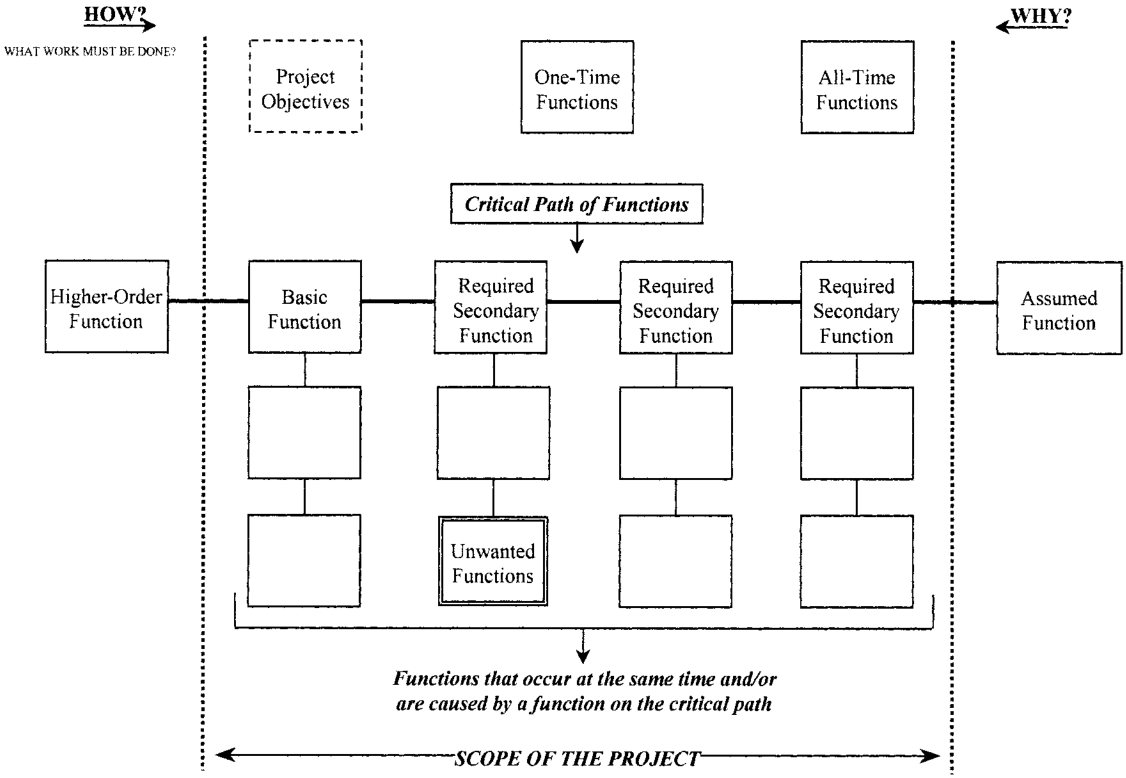

HOW?
WHAT WORK MUST BE DONE?
WHY?
Project Objectives
One-Time Functions
All-Time Functions
Critical Path of Functions
Higher-Order Function
Basic Function
Required Secondary Function
Required Secondary Function
Required Secondary Function
Assumed Function
Unwanted Functions
Functions that occur at the same time and/or are caused by a function on the critical path
SCOPE OF THE PROJECT

FIGURE 13.3.4 Function analysis system technique diagram.

The most important aspect of a FAST diagram is constructing the critical path. This is accomplished by first placing the basic function just to the right of the left-hand scope line on the critical path. Then, ask the question, "Why is the basic function performed?" The function that answers this question is the higher-order function. This function is placed to the immediate left of the left scope line. In order to check the validity of the selection of the higher-order function, ask the question, "How is the higher-order function accomplished?" The answer, with respect to the project being studied, should be the basic function.

All other functions on the critical path will lie to the right of the basic function. To determine the proper arrangement and relationships of the functions on the critical path, continue to ask the two basic logic test questions: "how?" and "why?" Using the how test, key on the basic function and ask the question, "How is the basic function accomplished?" The function answer should be placed to the immediate right of the basic function. The how question can also be asked, "What work must be done?" The second test of why works in the opposite direction. Ask the question, "Why do I (verb) (noun)?" The answer should be the function to the immediate left on the critical path, in this case the basic function.

Continue building the critical path by asking how-why questions until you reach the right-hand scope line. The function that lies on the critical path and to the right of the right-hand scope line is called the *assumed function.* The assumed function is outside of the study scope. The team must assume that this function is occurring properly and focus its attention on the functions that it can affect. Typically, the critical path between the scope lines includes no more than five functions. If there are more than five functions on the critical path, the team may have laid out a time sequence of functions and should reevaluate their how-why logic.

Once the critical path has been developed, the other secondary functions the product performs are distributed on the FAST diagram. If the unassigned functions "occur at the same time" and/or "are caused by" functions on the critical path, place these functions below the appropriate critical path function. If some of these functions are "unwanted" secondary functions, they are highlighted by placing a double-lined box around the functions.

When a function is directly related to more than one critical path function or happens "all the time," such as an aesthetic function, it is placed above the critical path functions in the upper right corner of the diagram. Functions not directly related to critical path functions that occur "one time," such as setup, assembly, and packaging functions, are placed in the middle of the diagram above the critical path. If there are specific "project objectives" the team wishes to keep in mind as the FAST diagram is constructed, place them above the basic function in dotted boxes.

Cost-Function Relationships. Cost-function relationships provide direction for the team related to areas of greatest opportunity. In other words, the team is able to identify which functions are not providing good value. Figure 13.3.5 shows an example of a cost-function worksheet. The functions within scope are listed across the top of the form. Then the major cost groups (from the cost visibility worksheet or sequence flowchart) are listed down the left-hand side of the form with the associated incremental costs in the total cost column. Next the function(s) impacted by each part or subassembly is identified. Once this is done, the team must estimate how much of the cost of each part or subassembly belongs to each function. This need not be a precise estimate. Finally, all columns are added vertically to determine how much cost is allocated to each function. Typically, three or four functions will be responsible for 60 to 80 percent of the total cost. The percentage of the total cost that each function represents is then transferred to the FAST diagram for further analysis. Examples of this are shown in Figs. 13.3.6 and 13.3.7.

Identify Functions Requiring Improvement. Having completed this step, the team is ready to key on specific functions and develop additional alternatives. Typically, less than 20 percent of the total cost is related to the basic function. However, this is what the customer wants to buy! The areas of potential cost improvement are generally obvious by simple review of the costed FAST diagram. It is equally obvious that several functions do not require any attention because their cost contribution is relatively small.

Cost is not the only consideration used to determine functional areas needing improvement. Quality, reliability, customer satisfaction, and productivity are also critical criteria. Problems in any of these areas need to be related to the functions. The final decisions regarding which functions the team should focus on are based on a combination of the cost-function analysis, the relative importance of the functions as shown on the FAST diagram, functions that dominate in quality, reliability, or customer satisfaction concerns, and functions that are non-value-adding or unnecessary.

Evaluation Techniques

The purpose of the evaluation phase is to systematically reduce the large number of ideas generated during the speculation phase to a number of concepts that appear promising in meeting the project's objectives. During the evaluation phase, the obvious nonsense ideas that were developed during brainstorming sessions will be eliminated, the ideas will be organized into logical groupings and analyzed with respect to project criteria, and the best combination of ideas will be identified.

Determine Evaluative Criteria. It is important for the VM team to be fully aware of the specific objectives for the project. These objectives will guide the VM team in their development and documentation of the evaluative criteria for the idea developed. These criteria must represent what is important to the customer and management. Then the ideas can be evaluated on the basis of how well they satisfy these criteria. The recommendations for improve-

Item	Total cost	Transmit force	Convert energy	Transmit torque	Direct fluid	Receive torque	Contain pressure	Restrict travel	Dampen shock	Adjust length	Allow attach	Shield container	Receive fluid
	Steering Gear												
Valve assembly	23.53		5.25	3.75	4.88	1.65	4.50				3.50		
Housing assembly	35.86	20.45			11.85			1.80			0.80	0.10	0.86
Tie rod assembly	27.49	20.39						0.60		3.00	3.50		
Tube assembly	7.26	2.90	2.56								0.60	1.20	
Rack	14.78	5.33	9.45										
Bellows	1.90											1.90	
Rod bushing	3.21		2.90									0.31	
Rack guide	3.59	2.75						0.70	0.14				
Housing cover	1.19											1.19	
Final assembly	8.82	1.75	2.20		1.37	1.80	0.20	0.20		0.25		0.15	0.90
Scrap	3.44	0.15	1.93	0.75	0.05		0.18			0.30			0.08
Total	131.07	53.72	24.29	4.50	18.15	3.45	4.88	3.30	0.14	3.55	8.40	4.85	1.84
%	100.0%	41.0%	18.5%	3.4%	13.8%	2.6%	3.7%	2.5%	0.1%	2.7%	6.4%	3.7%	1.4%

FIGURE 13.3.5 Cost/function worksheet.

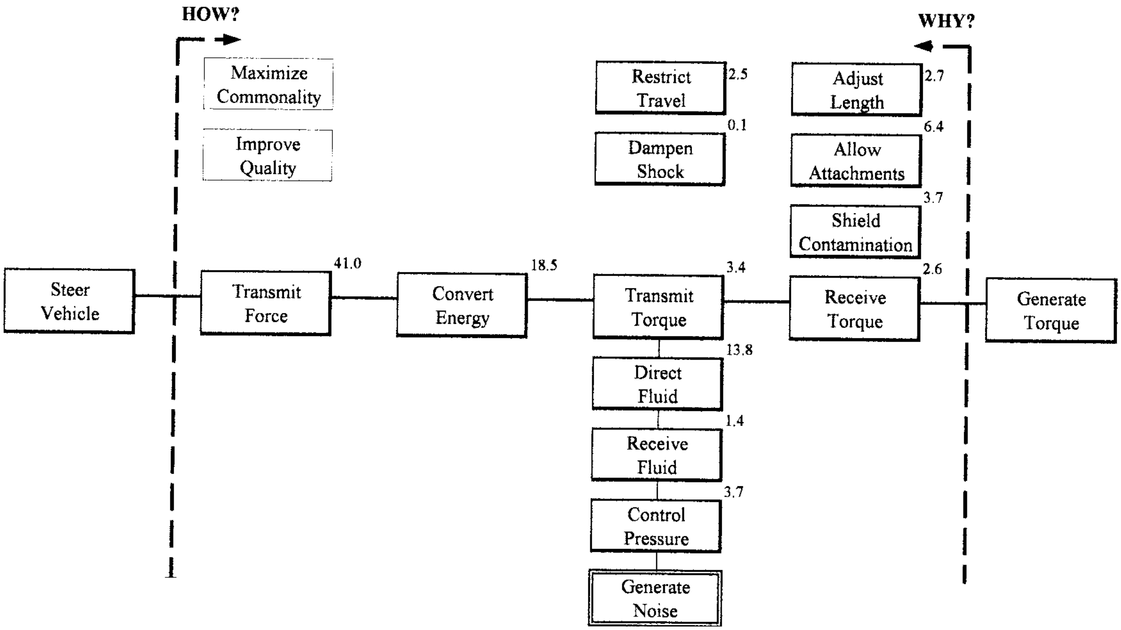

HOW?
WHY?
Maximize Commonality
Improve Quality
Restrict Travel
2.5
Dampen Shock
0.1
Adjust Length
2.7
Allow Attachments
6.4
Shield Contamination
3.7
Steer Vehicle
Transmit Force
41.0
Convert Energy
18.5
Transmit Torque
3.4
Receive Torque
2.6
Generate Torque
Direct Fluid
13.8
Receive Fluid
1.4
Control Pressure
3.7
Generate Noise

FIGURE 13.3.6 FAST diagram—steering gear-hydraulic assist.

ment that result from the VM study will have a greater probability of being implemented and causing the desired effects if the evaluation criteria is properly identified.

Evaluate Ideas. This step in the evaluation process consumes the most time and energy. With the evaluative criteria agreed to, the ideas are evaluated one at a time. To evaluate an idea, the team must first conceptualize the idea and determine how it can affect the project. Often sketches are made, prints are reviewed, and the idea is discussed by the team to allow all members to thoroughly understand the concept.

Once the concept is thoroughly understood by the team, it is beneficial to test the idea with respect to the most important criteria. The idea evaluation form is used for this purpose (see Fig. 13.3.8). The five columns preceding Advantages rate the ideas for the critical customer criteria. These criteria vary from project to project. Ideas are rated on a five-point system with a maximum of +2 points and a minimum of –2 points. VM recommendations with a –2 point rating for any critical criteria should not be developed or presented, unless directed by the client, because of serious budget problems.

The rating system is as follows:

+2	Significant improvement
+1	Some improvement
0	No significant change
–1	Slight degradation
–2	Significant degradation

After the critical criteria have been tested, the team can identify other advantages and disadvantages of the idea. The positive features of the concept are listed first. The list may include

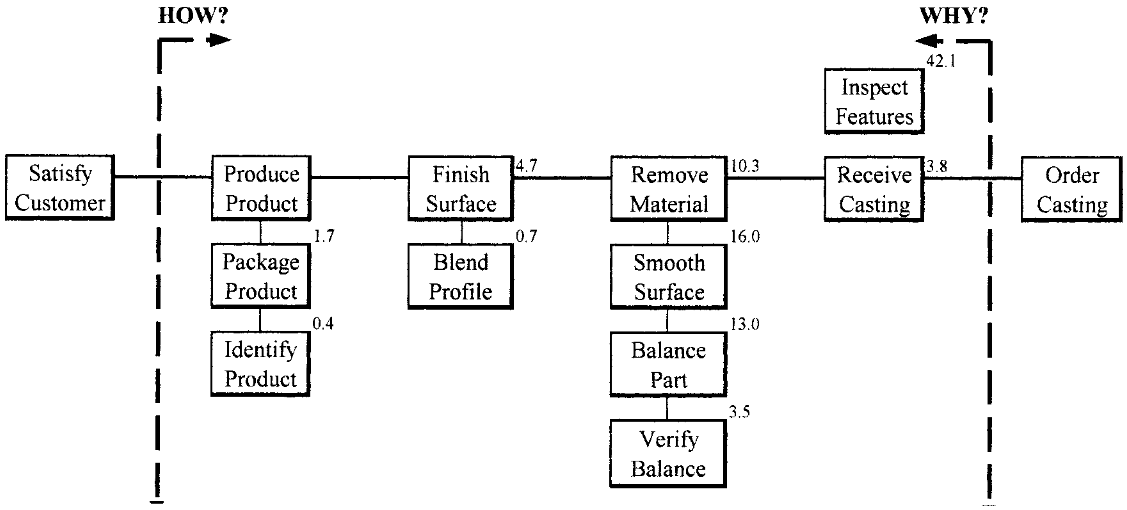

HOW?
WHY?
Satisfy Customer
Produce Product
Finish Surface
Remove Material
Receive Casting
Order Casting
Inspect Features
Package Product
Identify Product
Blend Profile
Smooth Surface
Balance Part
Verify Balance
42.1
4.7
10.3
3.8
1.7
0.7
16.0
0.4
13.0
3.5

FIGURE 13.3.7 FAST diagram—compressor wheel, processing.

not only technical benefits, but also such considerations as acceptability by the customer or user, similarity to known or current processes or designs in use, degree of risk, or ease of implementation.

Once the team members have listed all the positive ideas they can think of relating to the concept, they must challenge the concept and identify the potential problems or concerns, listing any negative aspects of the idea. Caution must be used. Just because some negative or potential problem features are listed, do not take the attitude that the idea will automatically be eliminated. Rather, analyze the idea to see if the negative features can be overcome or at least reduced to a tolerable level. Typically, the negative features will be of two types: people or technology. By looking at them closely, the team may be able to improve the concepts by reducing or eliminating the negative impacts.

Once this is completed, the ideas are rated for development. This rating system is based on a scale of 1 to 10 as indicated by this rating index:

10 Technically feasible—the project will benefit greatly. Significant cost and/or significant functional improvements.
9 Technically feasible—will improve the project. Some cost and/or other functional improvements.
8 Technically feasible—minor cost and/or other functional improvements.
7 Could have some project benefits—but will require additional analysis to verify if cost and/or functional improvements are possible. May challenge design criteria. Needs further development.
6 Alternate approach—but no significant benefits. Possible design suggestion.
5 Cost reduction—some loss in functional requirements.
4 Benefits questionable.
3 Too many unknowns to pursue further.
2 Significant disadvantages.
1 Does not meet program requirements.

		Criteria							
No.	Creative idea	$	C	Q	M	S	Advantages	Disadvantages	Rank
1	Remove screws from handle halves and replace with interlock feature.	+1	−1	−1	+2	0	Faster, easier assembly Lower cost	Could result in noise from vibration when operating Customer concern—need to test	7
2	Mold color into adjustment knob to eliminate the secondary silk screening operation.	+2	+1	+2	+2	0	Better, more consistent appearance Reduces processing steps	May need to resource supplier and change material	9
3	Improve friction fit of adjustment knob in order to eliminate the use of adhesive.	+1	−1	0	+2	0	Reduces final assembly time, one assembly station Avoids cleanup and maintenance to adhesive machine	Must ensure knob is as secure as current method High potential for customer to lose knob if it comes off	7
4	Replace snap ring and two screws with orbital rivet.	+2	−1	−1	+1	−2	Improves bottleneck in assembly process	Ability to maintain quality with rivet questionable Service could damage the part removing the rivet	4
5	Shrink-wrap on card instead of packaging in individual boxes.	+2	?	0	+2	0	Greatly reduces packaging cost and time to package	Use may be limited to entry level model due to customer perception	7

Evaluation criteria: Significant improvement +2, +1, 0, −1, −2 Significant degradation
$ = Construction cost C = Customer impact Q = Quality M = Manufacturability S = Serviceability

FIGURE 13.3.8 Idea evaluation.

Based on the total rating, ideas rated positively are developed further and documented on the Value Management Alternative form.

Comparative Analysis. Traditionally, choices between potential alternatives are selected on personal, subjective mental weighing of the criteria and risk. When this happens, one particular criterion often overpowers the rest, and the ultimate decision is often not the best decision for the company or customer. When deciding whether to implement change, management is faced with substantial investments of money and time. Thus management needs to evaluate the alternative with respect to all of the criteria to make the proper decision.

To respond to these needs, a matrix analysis based on utility theory for selecting the best value alternatives was developed. It is a mathematics-oriented process, which reduces much of the subjectivity of comparative analysis. Further, it is capable of combining benefits, evaluating resource mixes, and comparing potential alternatives for implementation. This matrix has been refined to incorporate the definition of value representing the ratio of performance, delivery, and cost.

The matrix is an effective tool in evaluating alternatives, since diverse criteria such as reliability, customer needs, quality, and implementation requirements can all be incorporated into the analysis and recommendations. This approach can provide management much better information to aid in their final decision.

Determine Performance Criteria. The initial step is to recognize and define needs. Too often, product and service decisions are based on what an organization can best design and produce rather than what the customer needs. That situation causes a value mismatch and will result in loss of business. Determining the performance criteria will require gathering information from throughout the organization and, most important, from the customer.

Determine Relative Importance of Each Criterion. Two steps are important to the determination of the final outcome—the selection of criteria and the relative weighting (importance) of these criteria. Of these two, selection of criteria presents fewer problems. Various management sources can decide which criteria should be used for internal reasons, and market research can determine which factors and/or features the customer wants. The basic question is, "How important is each criterion in relationship to the other?" For instance, engineering might state that reliability, weight, and performance are essential; manufacturing may want the decision based on producibility and quality; marketing may favor appearance, delivery, maintainability, and so on. The essential task is to determine the relative importance of the factors. Is reliability twice as important as weight? Is delivery half as important as quality? Is producibility equal to appearance?

While many different approaches can be used to determine the weighting factor, the *paired comparison method* is one of the most effective. This method is based on the assumption that the simplest and least emotional decision considers only two criteria at a time and determines which is more important. In essence, it only requires an answer to "Is criterion A more important than criterion B?" rather than a judgmental "How much more important is criterion A than B?" choice. By comparing each criterion against the other in this fashion, the relative importance of each criterion is easily established. A paired comparison matrix (Fig. 13.3.9) is an effective way to record and tally the decisions.

In this example, the team identified six criteria as important to the final decision. The letter in the box relates to the letter code of the criteria that the team considered the most important in the decision between the related pair of criteria. The number of times each criterion was selected is totaled by counting the number of times A, B, C, and so on occurred, and entering that quantity in the Total column. Note that each letter can occur in only one row and one column. Once the totals for each criterion have been determined, percentages can be calculated and the contribution that each criterion has to the total decision can easily be determined. One criterion will always be 0. This does not mean that the criterion is not important, rather that it is just the least important, and all alternatives must meet the minimum acceptable level for this criterion.

When using this technique, it is essential that the customer's opinion of criteria and relative importance be considered in the process. This will help the team avoid a value mismatch between the producer and the customer.

							TOTAL	%
RELIABILITY	**A**	a	a	d	a	a	4	27
SERVICEABILITY		**B**	c	d	b	f	1	7
PRODUCIBILITY			**C**	d	c	f	2	13
QUALITY				**D**	d	d	5	33
WEIGHT					**E**	f	0	0
EASE OF USE						**F**	3	20

FIGURE 13.3.9 Paired comparison matrix.

Rate Alternatives. Once the relative importance of the criteria has been determined, each alternative is rated for each criterion. The most effective way to rate the alternatives is to rate each alternative for one criterion before proceeding to the next criterion. To accomplish this, a consistent scale of measure should be used. In practice, any scale will work as long as the same scale is used for all the criteria. An easy scale to use is 1 to 10, with 10 being excellent and 1 being poor.

Compute the Total Score for Each Alternative. The total score for each alternative is computed by multiplying the weighting established times the rating by criterion for each alternative and summing the totals. Figure 13.3.10 illustrates the process using three alternatives and the current method.

Estimate the Cost of Each Alternative. Based on the organization's normal estimating practices, the predicted cost of each alternative is determined. Cost estimates for the alternatives are often developed from historical data or variations to the current design. Implementation cost is not included other than how it might affect the recurring manufacturing costs.

Compute the Value Ratio. Value can be determined by the relationship

$$\text{Value} = \frac{\text{performance and delivery}}{\text{cost}}$$

Thus dividing the total weighted factors for each alternative by their estimated cost will provide a ratio indicating the best total value alternative.

Evaluative criteria	Weight of importance	Idea A		Idea B		Idea C		Current method	
Reliability (MTBF)	27	4	108	7	189	7	189	5	135
Serviceability (MTTR)	7	5	35	7	49	9	63	8	56
Producibility (TTP)	13	9	117	7	91	8	104	6	78
Quality (rejection rate)	33	4	132	8	264	9	297	7	231
Ease of use	20	5	100	8	160	6	120	7	140
Total weighted criteria	100		492		753		773		640
Estimated cost			13.50		15.00		20.00		22.00
Value ratio = criteria/cost			36.44		50.2		38.65		29.09

FIGURE 13.3.10 Comparative analysis matrix. MTBF, mean time between failures; MTTR, mean time to repair; TTP, time to produce.

Select the Alternative that Offers the Best Total Value. Although alternative A has the lowest cost and alternative C has the highest criteria total, alternative B offers the best total value based on the ratio of performance and delivery factors to cost. Use of the evaluation matrix procedure provides an easily understood and administered process for orderly decision making. This technique avoids the potential of one criterion dominating the others. Allowing cost to dominate the decision might result in alternative A being selected or, if quality dominated the decision, alternative C might be selected. Neither of these decisions represents the best overall decision for the company or the customer. This method not only reveals strengths and weaknesses of each alternative, but also shows where improvements in individual factors could significantly impact the final decision.

WHY VM WORKS

Value management has been a successful management tool for over 50 years, and even today its application continues to grow and expand. Its success can be traced to many factors, but the key factors are focus, communications, multidisciplinary team approach, and the function analysis/FAST diagram techniques.

Focus

The VM job plan keeps the team focused on the task at hand and guides the team logically through the analysis to the appropriate conclusion. This focus also results in the reputation VM has earned for providing fast solutions to problems and effective use of corporate resources. At the conclusion of one VM study, the team stated that they had accomplished in one week what would have normally taken nine months to do with traditional methods.

Communications

Each VM technique serves to facilitate a particular and needed analysis of the project. However, each technique also serves a higher-order function—that is, to facilitate communication between the team members to enhance the total understanding of the project and build consensus for the needed improvements.

Multidisciplinary Team Approach

Representatives of the L. D. Miles Value Foundation have researched and found that VM was one of the first management processes that employed the multidisciplined team approach that is in widespread use today. The traditional synergistic effect of a team is multiplied when the team members are from varied disciplines and can develop a companywide, rather than a departmental, perspective for a project.

Function Analysis/FAST Diagram

The function analysis techniques are what separate VM from other management processes. Function analysis forces a different perspective on a project and provides a unique communication tool that allows people without specific knowledge of the technical aspects of a project to effectively participate in and contribute to the study. The FAST diagram further deepens the understanding of the project by the team and allows the team to verify the functional requirements for the project.

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BIOGRAPHY

Terry Hays, C.V.S., is a management consultant and president of Value Management Strategies, Inc., in Escondido, California. He has been a VM consultant for over 15 years. He has extensive value engineering experience, having directed over 2000 teams in value engineering studies on product designs, manufacturing processes, procedures, strategic plans, a wide variety of construction projects, and management problems. Prior to working as a management consultant, Hays spent 17 years with the General Motors Engineering Staff and Cadillac Division and 2 years for Hoover Universal—Automotive Products Group. He received his B.S.M.E. from Lawrence Technological University in Southfield, Michigan. He is a Certified Value Specialist and has held numerous national and local offices in SAVE International, the Value Society. He is also a member of the Society of Automotive Engineers (SAE).

Source: MAYNARD'S INDUSTRIAL ENGINEERING HANDBOOK

CHAPTER 13.4

QUALITY MANAGEMENT

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Quality is no longer the discriminating mark of an expensive product. It is an absolute prerequisite for survival, for all products and services.

Quality doesn't happen by accident, it must be purposely initiated and managed. It cannot be added as an afterthought late in the process—it must be taken into consideration from the beginning. Managing quality cannot be limited to the actions of an inspection or a quality assurance department. It is the responsibility of all departments and individuals involved in designing, planning, engineering, producing, and distributing the products.

Quality management is about the actions and activities necessary to define, plan, implement, control, and improve the quality of our products and services. This chapter examines the elements of quality management, gives an overview of the methods and tools used, and describes in some detail the application of the more important methods and tools from the viewpoint of an industrial engineer.

INTRODUCTION TO QUALITY MANAGEMENT

About Quality

The quality of a product—or a service—is its ability to satisfy the needs, requirements and expectations of the customer. Product quality includes technical characteristics such as performance, reliability, durability, serviceability, and conformance to standards and specifications, but also more subjective characteristics such as styling, feeling, sound, and even smell. Service quality has characteristics such as performance, timeliness, and conformance to specifications. The quality of a process is its capability to produce products or services with the intended characteristics.

From Inspection to Quality Management

When products were made by craftspeople and artisans, checking the product obviously was done by the artist. With the evolution of industrialization and mass production, inspection developed into a separate task performed by specialized inspectors. The adoption of the Taylor system and the priority given to ever increasing productivity tended to have a negative effect on quality, which was met by the introduction of the central inspection department. As statistical methods were introduced, industrial metrology and inspection technology developed and new disciplines such as reliability engineering evolved; these new tasks were assigned together with the central inspection department to a new functional organization called quality control or quality assurance.

While the centralized quality function usually served its highest priority purpose quite well—protecting the customer from bad quality—it was less well placed to improve the quality of the production processes. Even worse, its success in protecting the customer led to a widespread belief that the quality function, not the production departments, was responsible for the quality of the products. Worst of all, however, was that top management tended to relinquish its responsibility for quality, believing that they could delegate this to quality assurance.

As a consequence, nobody but quality assurance felt any responsibility for quality, and they could not do very much about it because they had no control over product design and process engineering and very little over the production processes—and they, of course, lacked the overall power of top management. In far too many companies this led to a situation where unrealistically designed products were manufactured in incapable processes by poorly trained and informed operators and inspected and repaired under constant pressure to get them shipped as soon as possible. The net result was doubtful product quality, late shipments, and horrendous costs for time, material, and labor squandered.

Gradually, under the pressure from growing competition, it began to dawn on industry that most business areas and departments within the company had some influence on quality, and that their decisions and actions with regard to quality had to be coordinated. Top management began to understand that quality was of crucial importance for the success of the company, and that quality was a management responsibility. Quality had to be managed.

Building Blocks of Quality Management

The two classic components of management are considered to be planning and control. Because no management situation is static, improvement and development must be added, as well as information, without which no action is possible. In similar fashion, the components of quality management are quality planning, quality control, quality improvement, and quality information.

Quality planning includes the activities necessary to define and specify the intended quality of a product or service, as well as the consequential requirements on product design, process design and manufacturing engineering, process control, and product inspection and test.

Quality control includes all activities necessary to make sure that products meet all requirements and that processes meet their specifications.

Quality improvement includes the activities necessary to identify improvement needs and opportunities, to define and implement improvement actions, and to verify their effectiveness.

Quality information includes all the information, internal and external to the company, that is needed for the quality planning, control, and improvement processes.

Quality Management Systems and Systems Standards

A quality management system comprises the organizational structure with authorities and responsibilities, the technical and managerial procedures and processes, and the resources necessary to implement coordinated quality management in a company.

A quality management systems standard describes the minimum requirements on a documented quality management system. Standards exist for systems of different levels and complexity. The first such standards were issued by military procurement agencies, soon followed by regulated industries such as the electrical and automotive industries. General quality management systems standards have been issued by various standardization organizations. The best known and most widely applied is the ISO 9000 series, which is discussed in detail in a separate chapter of this handbook.

The implementation of and certification to a standard such as ISO 9000 has the great advantage of assuring that the organizational framework for coordinated management of quality is in place. The standard per se does not create quality—only people can do that—but it constitutes a good platform on which to build the quality work.

TOTAL QUALITY MANAGEMENT

Concepts and Characteristics

In the 1980s, among practitioners of quality management and people who did research and consulting in this management area, a new concept evolved under the name of total quality management or TQM. The concept was strongly influenced by the experience of high-quality products from Japanese manufacturers and by what had been learned about Japanese approaches to quality management.

The philosophy of TQM is that quality is a top management responsibility, customer satisfaction is the primary target, continuous improvement is the credo, and the way of action must be based on facts, not opinions, and all employees are involved.

The strategy for TQM is to concentrate on simplification and improvement of processes, organize action around supplier-customer relations (external as well as internal), use cross-functional, interdisciplinary teams for improvement and problem solving, monitor and act on internal and external quality information and comparisons with competition, and train all employees in TQM philosophy and methods.

TQM Applied

Introduction of total quality management in an organization, whether a manufacturing or service company (e.g., a utility or hospital), in most cases is a wrenching experience because it usually means major changes not just in operational modes and work habits, but in ingrained opinions and even in the culture of the organization. It is not surprising that many attempts to introduce TQM have consequently failed miserably. On the other hand, there are many examples of companies and other types of organizations where the introduction of TQM has been an unqualified success.

With some simplification it can be stated that companies that have successfully implemented TQM had three things in common:

1. There was a shorter- or longer-term threat to their survival.
2. They all had CEOs who personally took the lead in the TQM introduction and implementation.
3. They all invested heavily in training and coaching their managers and all other employees.

Typically, introduction of TQM would have to start with top management developing an understanding of the company's situation and prospects, followed by their generating a new strategy, setting corresponding targets, and defining plans and resources for its implementation. Next, all employees would be involved through interactive sessions where the company's situation, the new strategy and targets, and the plans for implementation would be discussed. The objective of these sessions would be not just to inform the employees but to develop insight and a positive attitude toward the changes and the implementation to come.

Next, quality improvement teams would be set up, starting with a few bellwether ones, in different areas and at different levels of the company, each to investigate and improve a specific operation or process. Before and during the improvement project, the team members would be given training and coaching in those specific methods and tools needed for their specific project. Information about ongoing team projects and their results would be disseminated throughout the company, and successful teams would be given visible recognition and rewards. Properly managed and given enough support, this process should result in a large number of improvement teams and a large percentage of the employees trained and involved, as well as an accelerating positive effect on quality and productivity.

Some of the teams would be interdepartmental and interdisciplinary, working on larger or more complicated processes. Many others, however, would be largely constituted by workers taking on projects within their own working area. Through these local teams it would be hoped that the habit of continuous improvement would spread in the organization. Regardless of where or at what level the teams operate, the tools they use are the same, as outlined in the subsequent section, Methods and Tools.

Looked at in a more structured way, TQM incorporates three categories of systems: strategic, cultural, and technical. The strategic systems include policy and objectives deployment, benchmarking and business information systems, while the cultural systems comprise an adaptive culture—"the learning organization," education and training, cross-functional capability development, performance feedback, and recognition and reward systems. The technical systems, finally, include methods and tools such as problem solving, statistical process control, quality function deployment, failure mode and effect analysis, concurrent engineering, and design of experiments—as well as methods and approaches covered elsewhere: just-in-time (JIT) and total preventive maintenance (TPM).

Precursors of TQM

Total quality management's appearance in the 1980s wasn't sudden and unexpected, it had a long gestation period and several godfathers. Its inception could probably be attributed to A. V. Feigenbaum, who recognized the necessity of involving all functions of the company in the process of creating, maintaining, and improving quality. In 1957, he coined the expression *total quality control* for this concept; this was also the title of his pioneering book in 1961.

J. M. Juran very early recognized that quality is a management responsibility and must be systematically managed. He is generally considered the originator of the concept of quality management with its three components of quality planning, control, and improvement. He identified the different organizational requirements for control and improvement, and defined the process for achieving breakthrough. Beginning in 1954, he lectured extensively to top management in Japan, where he was received as an authority and a guru. He is credited with playing an important role in laying the groundwork for the success of Japanese quality. Through many years of inspiring lecturing, he has had a strong influence on the quality movement in Europe and the United States, and he was instrumental in the development of TQM in the western hemisphere.

W. E. Deming has been given even more credit than J. M. Juran for the remarkable development of quality in Japan, where he was lecturing on statistical process control in the early 1950s. The methods he taught were developed in the 1920s and 1930s in the United States, but they never were widely applied. Only when TQM started to break through in the 1980s, were these methods used extensively in the United States. Late in his life Deming finally received recognition in his home country, lecturing and consulting to top management in many of the largest U.S. companies, not just on statistical process control but also on his concept of quality management.

Evidently, many Japanese managers, consultants, and professors were involved in the quality movement in Japan. The best known was professor K. Ishikawa, who was lecturing and consulting on what he called *total quality control* for 40 years, beginning already in 1949.

If most of the statistical tools and much of the management concepts were imported to Japan from the United States, one very important concept—the most important characteristic of TQM—was developed in Japan. This concept called *kaizen* in Japanese is usually translated as "continuous improvement" and is built on two basic ideas. The first is that everything can be improved, at least to some small degree, and that many small improvements add up to a large one. The second idea is that everybody in every organization can contribute to some improvement, given the necessary training and the freedom to do so. When this concept permeates a company and its organization is adapted to handle it, a flood of improvements can be let loose, with enormous potential to improve quality, cost, and lead times, as well as motivation of the employees.

Quality Awards Based on TQM

Recognizing the enormous importance of quality for business in a competitive world, and the potential of TQM as a way of achieving quality, a quality award was developed and signed into law in 1987 under the patronage of the U.S. Department of Commerce. This award, the Malcolm Baldrige National Quality Award, is granted once annually to companies in recognition of quality achievement and outstanding quality management. Companies applying for the award are assessed based on a business model with the seven examination categories of leadership, information and analysis, strategic quality planning, human resources utilization, management of process quality, quality and operational results, and customer satisfaction. Based on this model, participating companies put together extensive documentation to support their applications. The applications and the backup documents are scrutinized and assessed by specially appointed impartial assessors, who award points according to a predeterminated scale. A number of the companies with the best points totals are then visited by teams of assessors, finalizing their assessments while observing critical issues on site. The award winner and the runners-up are then appointed by a central assessment board, and, finally, presented the awards by the President of the United States in a special ceremony.

Similar quality award models have been developed and implemented at state and local levels as well as in many other countries. Most prestigious of these is the European Quality Award. The Malcolm Baldrige National Quality Award and the many other similar award models have contributed much to improvement of quality in the western hemisphere, not just as an incentive for participating companies. An even larger and more widely distributed effect has been the practice of many companies and other organizations using the award models for their own internal assessment and improvement programs.

Related Approaches

Three other approaches to improvement, business process reengineering (BPR), just-in-time (JIT), and total productive maintenance (TPM), are addressed elsewhere in this handbook. In the context of TQM it should be mentioned, however, that these three approaches and TQM are not conflicting or incompatible. In fact, they are highly complementary and very similar.

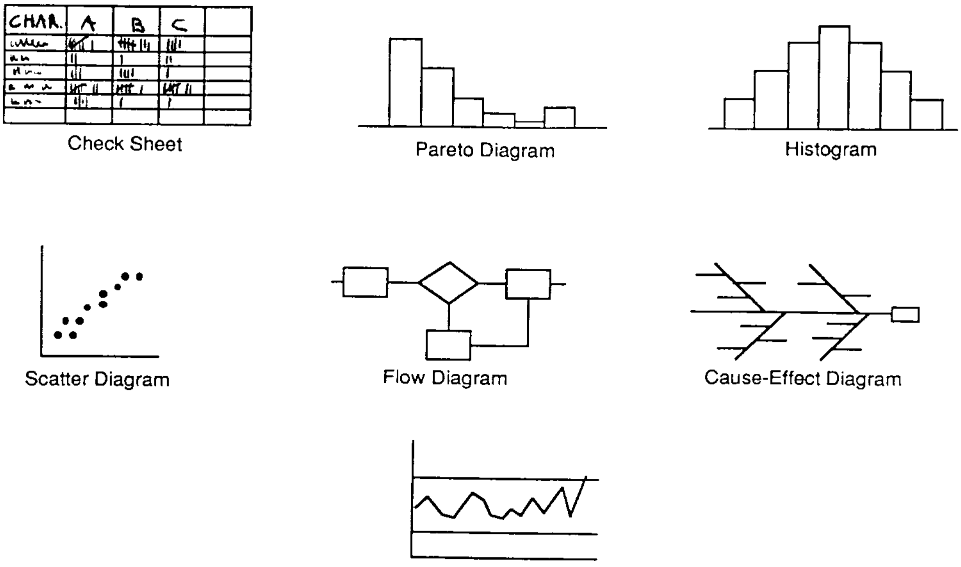
They are similar because all these concepts share a holistic view, stress the importance of management commitment, are strongly customer and process oriented, and are obsessed by elimination of waste. With the exception of BPR, they are driven by continuous improvement and stress the long-term perspective, while BPR is more short term and project oriented. Finally, the tools used are very similar. This results in a great potential for integration of efforts and mutual support between different improvement projects and processes.

METHODS AND TOOLS

The methods and tools described here are in most cases well known from other areas of application, while a few have been developed specifically for quality management purposes. Some of the tools may seem so simple and natural as not to need this designation. However, simple or sophisticated, old or new, they have all proven themselves very useful.

Problem-Solving Tools

Seven Basic Tools for Quality Improvement. These largely very simple tools were popularized as the *Seven Quality Control Tools* by the Japanese, who found that a majority of the quality problems could be solved effectively using only these tools to collect and systematize information about the problems. The seven tools are illustrated in Fig. 13.4.1 and include



Check Sheet Pareto Diagram Histogram

Scatter Diagram Flow Diagram Cause-Effect Diagram

Control Chart

FIGURE 13.4.1 Seven basic tools for quality improvement.

Checksheet, or tally sheet, to collect and sort information on the problem under investigation.

Pareto diagram, to sort information on observations in frequency order so that the most important phenomena can be identified and prioritized. Vilfredo Pareto was an Italian economist who found the well-known 80/20 rule to be applicable to the distribution of income. Juran used his name to designate this diagram, which allowed the identification of what Juran called "the vital few" issues—the ones to prioritize.

Histogram, to sort information in equally wide classes to get a quick and visual indication of the frequency distribution of the data, or into different groups according to provenance or source of the data (stratification) to discriminate between different problem sources and identify the vital few.

Scatter diagram, to identify relationships between two different characteristics.

Flow diagram, or flowchart, to describe the process under investigation.

Cause-and-effect diagram, or fishbone or Ishikawa diagram, to display cause-and-effect relationships between various factors influencing the problem under investigation.

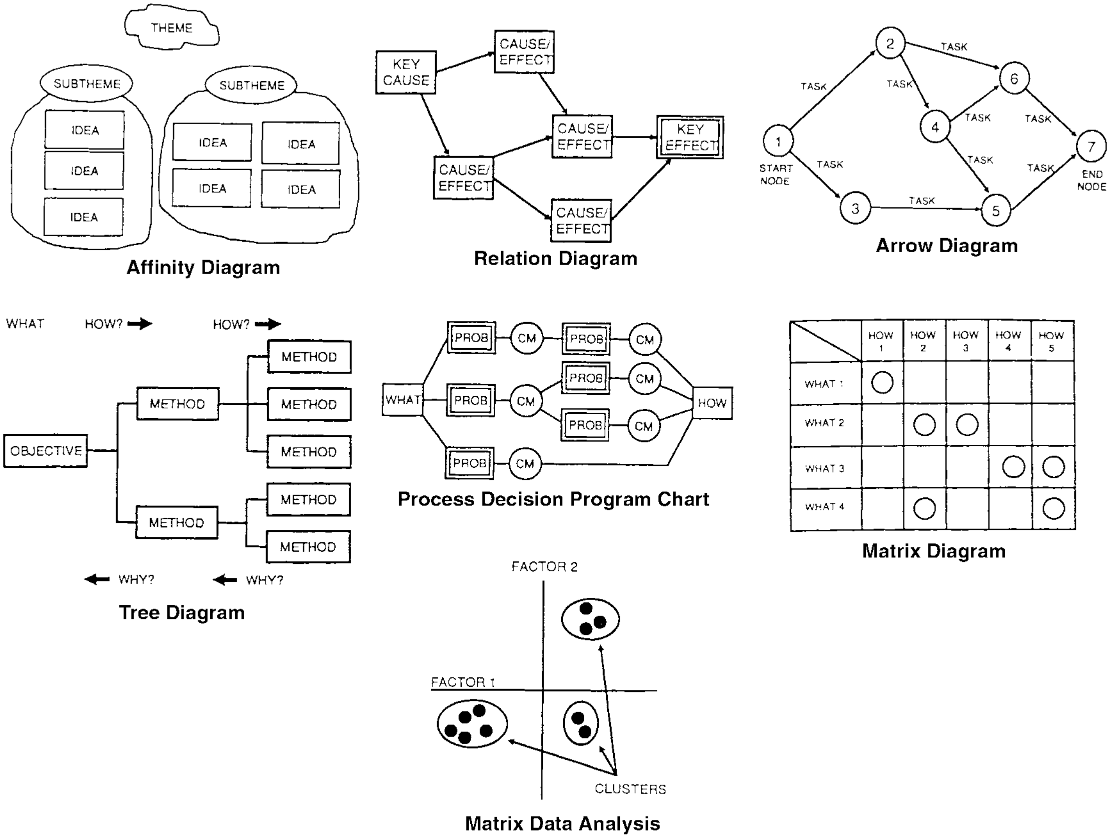
QUALITY MANAGEMENT

Control chart, to assess status and performance of a process under investigation, to provide warnings about abnormal conditions, and to trigger corrections.

These tools are primarily quantitative, used to process and find meaning from numerical data or to help identify what to investigate.

Seven Tools for Action Planning. These tools are primarily qualitative, used to assess and plan future activity and actions and measures to be taken. Also these tools have been given a Japanese designation, the *Seven New Tools,* although most of them have been well known for a long time because they were used in project management. As shown in Figure 13.4.2, these tools are

Affinity diagram, or K-J method or storyboarding, a method to collect verbal information—facts, ideas, and opinions—from a group of people and to organize it in categories of similar or connected contents, while simultaneously creating consensus about meaning and implications of the findings. The process starts with a collection of data, in most cases through brainstorming and individual writing of cards, which are pinned to a pin wall. The inputs are then discussed and changed as needed to achieve consensus on their validity, after which the cards are arranged into groups of similar items, always assuming discussion and consensus.


THEME
SUBTHEME
SUBTHEME
IDEA
KEY CAUSE
CAUSE/ EFFECT
KEY EFFECT
START NODE
END NODE
TASK
1
2
3
4
5
6
7
WHAT
HOW?
WHY?
OBJECTIVE
METHOD
PROB
CM
HOW
HOW 1
HOW 2
HOW 3
HOW 4
HOW 5
WHAT 1
WHAT 2
WHAT 3
WHAT 4
FACTOR 1
FACTOR 2
CLUSTERS

Affinity Diagram

Relation Diagram

Arrow Diagram

Tree Diagram

Process Decision Program Chart

Matrix Diagram

Matrix Data Analysis

FIGURE 13.4.2 Seven tools for action planning.

These groups are then given headers, characterizing their contents, and marked off by borderlines.

Relation diagram, to display complex interrelationships between ideas, actions, or objects, or to show cause-effect relationships in sequence.

Arrow diagram, better known as the critical path method, to map project steps in a time sequence and identify time critical tasks.

Tree diagram, to subdivide objectives into parts that can be acted on, or to break down tasks into subtasks, or to generate multilevel cause-effect relationships.

Process or program decision program chart, (PDPC), to identify potential problems in a planned process or program and determine potential countermeasures (CM).

Matrix diagram, to show different kinds of relationships between the characteristics or other items contained in two or more lists to document complex relationships and identify areas of special interest.

Matrix data analysis, to investigate multivariate data for hidden structure, map data into clusters, and identify segments.

These tools are typically used to create insight into new situations and future projects to enhance the probability of a successful outcome.

Interactive Problem Solving. Solving problems through quick fixes can—with luck—lead to fast improvements, although in most cases not with complete and lasting success. Applying the methods of what is generally known as continuous improvement takes longer but is more effective because the root causes of the problems are sought out and removed or neutralized. Furthermore, improvements are built into the normal system once; improvement action is ongoing and builds on previous results, and a wealth of common knowledge about problems, their causes and effects is built up in the organization for future use.

The so called Plan-Do-Check-Act (P-D-C-A) cycle is the foundation of continuous improvement and is often attributed to Deming, although it is really nothing but the normal steps of sound control of a project or an activity. You plan what to do, you do what you planned, you check the outcome, and you act on the result, either by establishing the improvement if the result is satisfactory, or by going through another improvement cycle if not.

Although the same principles apply when an individual undertakes to solve a problem alone, the problem-solving process is so much more effective when introduced in an interactive setting with a team of knowledgeable people. A team simply is more effective in finding the root causes and in developing a practical and effective solution, and quite especially, in implementing it. That's why problem solving here is described as interactive, in a team setting. The following steps are also shown in Figure 13.4.3.

1. Team formation—a team of knowledgeable people is selected and organized.
2. Problem definition—the problem is clearly and specifically defined.
3. Interim action—if necessary, a quick fix is determined and put in place as a stopgap solution while the permanent solution is sought.
4. Data acquisition—data is gathered in order to provide the needed factual information.
5. Data analysis—the data gathered is analyzed to develop an understanding about the problem, how and under what circumstances it occurs, and its effects.
6. Determination of scope and causes—detailed cause-effect relationships are determined; problem definition and scope may have to be changed based on what has been learned.
7. Determination of alternative solutions.
8. Evaluation of solutions—the alternative solutions are evaluated for effectiveness, cost, timing, implementation difficulties, and possible side effects.

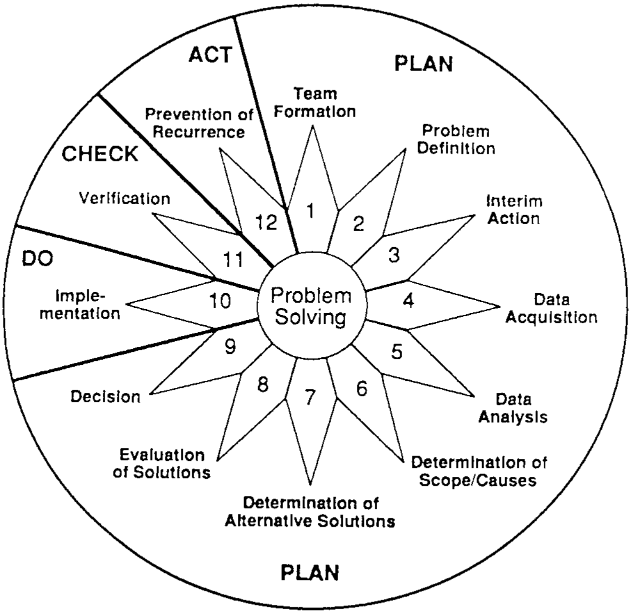

ACT
PLAN
CHECK
DO
PLAN
Problem Solving
1
Team Formation
2
Problem Definition
3
Interim Action
4
Data Acquisition
5
Data Analysis
6
Determination of Scope/Causes
7
Determination of Alternative Solutions
8
Evaluation of Solutions
9
Decision
10
Imple-mentation
11
Verification
12
Prevention of Recurrence

FIGURE 13.4.3 Interactive problem solving.

9. Decision—the final solution is selected and an implementation plan is developed.
10. Implementation—the solution is implemented according to plan and the results are established and documented.
11. Verification—the results are analyzed and reviewed. Any shortfalls may lead to a renewed problem-solving cycle or to definition of another problem to solve. Successful results lead to step 12.
12. Prevention of recurrence—the successful improvements are documented and built into the normal operation and its control system. The successful improvement is publicized and the team is given recognition for its efforts.

In this process, most of the time and effort is spent in analyzing and planning, which makes implementation swift, safe, and successful. The temptation to skip one or more of the steps must be resisted at all costs; jumping to conclusions is guaranteed not to solve a problem.

Statistical Tools

Everything in this world has a built-in variation, which we need to control to make the unpredictable predictable. The means to this end are the statistical methods and tools, some of which must be part of an industrial engineer's toolkit—or anybody's toolkit, for that matter. Of these methods and tools, some—basic statistics, statistical process control, analysis of variance and reliability theory—are discussed elsewhere in this handbook. A few others will be discussed here.

Process Capability Analysis. All real-world processes, manufacturing or other, have variation. If a process is stable and in control, its variation is described by a distribution, with a shape, a spread, and a location. Quite often, the distribution is normal, meaning bell-shaped with the mean at the center point and a symmetrical spread of three standard variations on each side of this center point.

The capability of a process is its ability to produce to the desired specifications. Evidently, a process with a smaller spread has a higher capability than one with a larger spread. However, a real-world process is chosen to produce a specific product with a given specification, including tolerances. That's why process capability (Cp) is expressed in relation to the tolerance width of the product in question. Basically, the tolerance width is divided by the process spread, i.e., the distance between the upper and lower specification limit (USL, LSL) is divided by six times the standard deviation of the process. This process capability assumes the process is centered around the midpoint of the specification, as in a couple of examples in Fig. 13.4.4.

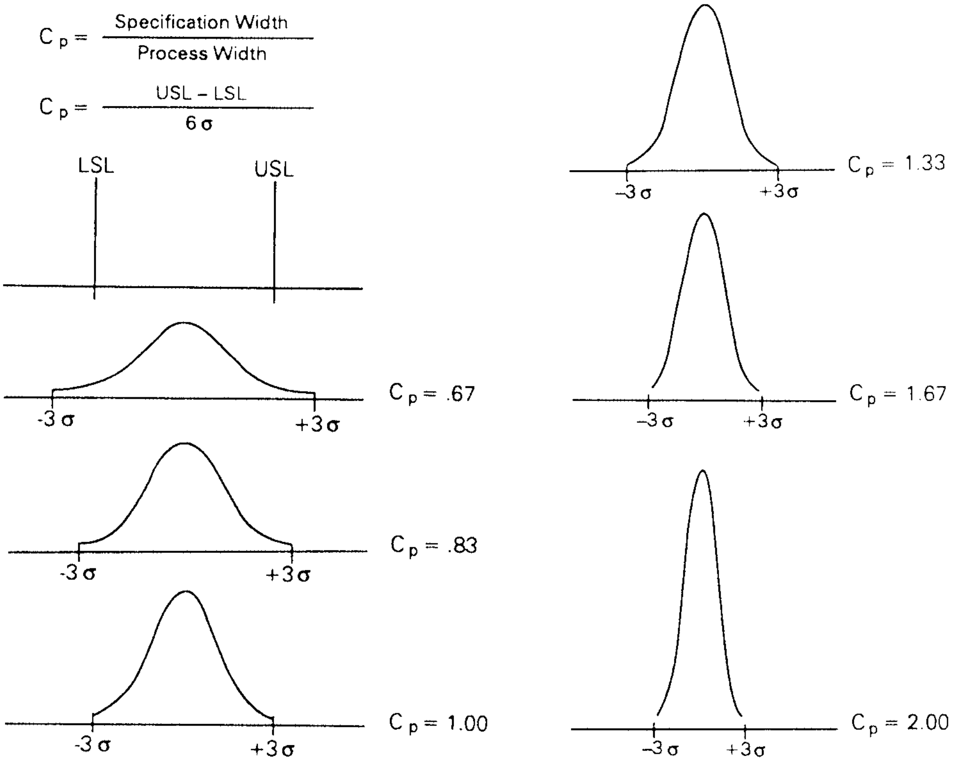


FIGURE 13.4.4 Process capability (Cp).

If, however, the process is not centered on the specification midpoint, as in Fig. 13.4.5, the process capability is reduced considerably and the expression for the process capability is somewhat more complicated; namely, distance between the mean of the process and the closest one of the specification limits divided by three times the standard deviation of the process.

The process capability values in Fig. 13.4.4 translate into numbers of defectives expressed in parts per million as follows:

capability value 0.90	means	6900 parts per million
1.00	means	2700 parts per million
1.33	means	66 parts per million

1.67	means less than	1 part per million
2.00	means	2 parts per billion

The data needed to calculate the process capability can usually be taken from the ongoing statistical process control, provided this is based on variables and, of course, provided the process is stable and in control. If the process control is based on attributive methods, a series of samples must be taken from the process and measured with regard to the important characteristics.

Design of Experiments. The outcome of a process (e.g., the yield of a chemical reaction or the tensile strength of hot rolled steel), is often influenced by many input factors. To decide at what level to set these independent variables in order to optimize the outcome is difficult and in most cases done based on previous experience, that is, what has been learned by trial and error. Another way of doing this is to set up a series of experiments where the input factors—the independent variables—are deliberately set at two or more different levels, and an experiment is run for each of the several combinations of all the independent variables while the resulting outcome is recorded. If the independent variables are very few, testing all combinations of them is a simple and straightforward proposition that leads to a fairly fast response.

If, however, as in most real-life situations, the number of input factors is more than just a few, the number of experiments necessary to test all combinations of these factors at different levels is very large, and the approach consequently is no longer feasible. This is where statistical methods can be applied, using *design of experiments,* or DoE, for an experiment designed to give a maximum of information from a minimum of experiment runs: that is, at optimal cost.

Intuitively one would tend to suggest an experiment where one of the factors would be tested at its different levels while all others would be kept constant. In this case, intuition would be wrong, however, for two reasons. First, this approach leads to a larger number of test runs than a properly statistically designed experiment, so it is too costly. Second, and more important, this approach totally disregards that the independent variables quite often are not all that independent. In most cases, one will find that two or more of the input factors influence each other mutually, creating what is called a covariance for these variables. If this effect is not taken into consideration in the design of the experiment, the results will be misleading and the conclusions may be completely wrong.

In a properly designed experiment, using the methods and mathematics of DoE, a limited number of variables will be tested at a few levels, usually two, in a limited number of runs. Which variables—input factors—to be included can often be decided based on available knowledge

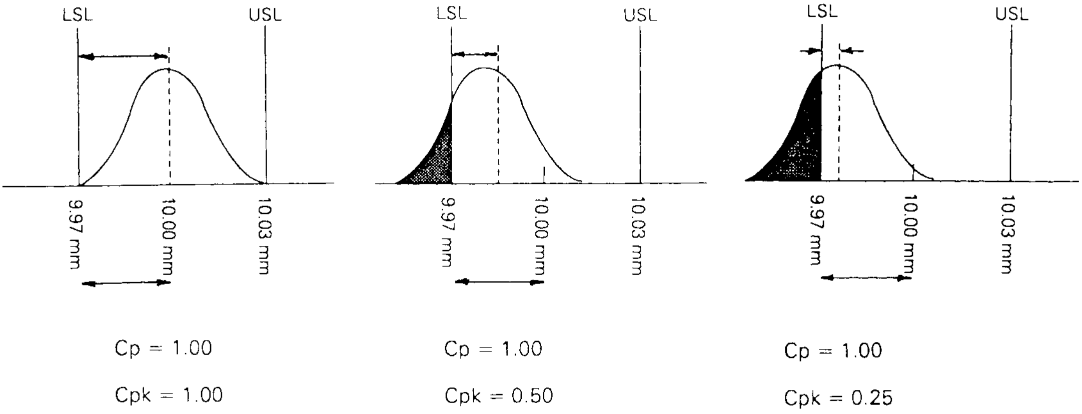


FIGURE 13.4.5 Process capability index (Cpk).

and experience; otherwise, a number of preliminary test runs can be used to assess which factors are important enough to be included. In most cases, relatively few of the factors have an appreciable influence on the result. This must be exploited to keep the number of runs as low as possible. It is also possible to keep the number of runs lower by reduced factor testing if it is known or can be safely assumed that no covariance exists between certain of the input factors.

Although DoE should be considered an important tool for improvement of processes with regard to productivity, costs, and lead times, as well as quality, these methods should not be applied casually. The mathematics and the details of application of DoE are complicated enough to be outside the scope of this chapter. Well-qualified and experienced specialists are absolutely necessary to introduce this powerful tool in any organization.

Taguchi and Robust Design. Kenichi Taguchi is a Japanese engineer and teacher, renowned for his quality philosophy and for his DoE methods. He makes a clear distinction between product characteristics, which are selected to satisfy the customer and make the producer competitive, and quality, which is determined by the deviation of the actual product characteristics, as produced, from the ideal of the specification. In other words, variation means bad quality and should be reduced as far as possible; the closer a process can produce to the nominal value of the specification, the better. Taguchi has even developed a concept for the cost of quality, essentially a second-degree function of the size of the deviation from the ideal or nominal value.

Recognizing that variation inherent to a process and disturbances from external sources cannot be eliminated entirely, Taguchi concluded that the product designs as well as the processes would have to be made robust, meaning less susceptible and sensitive to variation in characteristics and to external disturbances. He also devised a way to achieve this robustness, using DoE methods to seek an optimal combination of product and process specifications. This is performed in three steps, at the three consecutive levels of design: system, parameter, and tolerance.

In the first step, a complete system design of the product is drawn up and worked out in detail, resulting in a prototype that meets the customer's requirements and is producible, provided that no disturbances or deviations occur. As, however, deviations and disturbances do occur, provision for this is made in the second step.

Here the design parameters are determined, using known facts about the sensitivity of the intended product characteristics to changes in the parameters, for example, a nonlinear response. If no, or not enough, adequate knowledge is available, experiments must be run to determine such relations for the important parameters, using DoE methods.

In the third step, the tolerances are set, attempting to come as close as possible to the nominal parameter values. As in many cases the process capability sets definitive limits, a wider tolerance for one parameter may have to be offset by a more narrow one for some other parameter in the tolerance chain, where curtailing is easier to achieve.

Taguchi's DoE approach is an extension of the reduced factorial methods. To keep the total number of test runs as low as possible, the selection of factors to test is done by fully using all available knowledge and experience about the product and process at hand. This is especially so when it comes to deciding for which pairs of variables a covariance is to be assumed. Taguchi usually deletes pairs with weak correlation.

What was said previously about DoE generally applies even more for the Taguchi methods. It takes thorough knowledge and experience about products and processes to carry through the three-step design process, and it takes a very experienced expert to put together the test plan, execute the tests, and interpret the results. To describe in enough detail how this is done is outside the scope of this chapter.

Analytical Tools

In this section four methods, which have been described as *analytical* are presented, although strictly speaking all the tools presented so far are analytical because they are used to analyze

QUALITY MANAGEMENT

data of different kinds. The first three of the four are graphical, but so are several other tools, so that distinction is not very helpful.

These four methods—or tools—are used to analyze the interrelationships between the elements in a chain, or system, of product or process characteristics or components, in order to reach logical conclusions and answer questions like, "Given this, what then?" or "What if . . . ?"

Quality Function Deployment. *Quality function deployment* (QFD) is the not very apt English translation of the Japanese name for a *method,* through which overall requirements can be broken down to successively lower and more specific levels. The method was first developed in the Japanese shipbuilding industry, was adopted by the automotive industry, and has spread in the western hemisphere, prompted by the widespread implementation of TQM. QFD is usually used in connection with product development and the concomitant process engineering.

QFD is a graphical method, using a multidimensional form of the matrix diagram, which makes it possible to display even quite complicated relations in a clear way that is easy to understand. The starting point for phase 1 of a QFD analysis is a list of objectives—customer requirements, the WHATs that must be attained (see Fig. 13.4.6). These requirements are entered on the separate lines of the column on the left side of the matrix.

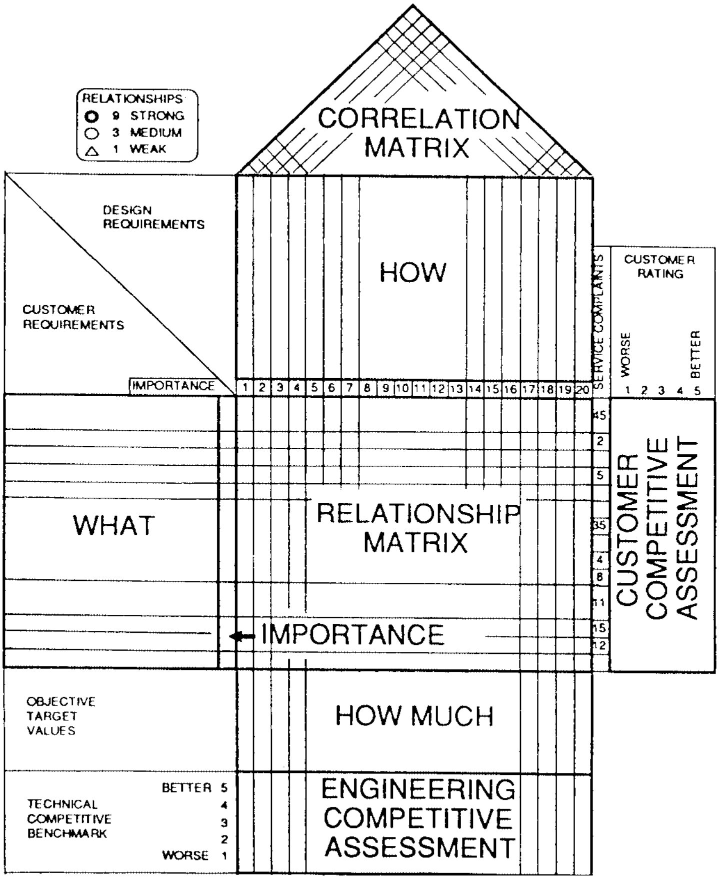

RELATIONSHIPS
9 STRONG
3 MEDIUM
1 WEAK
CORRELATION MATRIX
DESIGN REQUIREMENTS
CUSTOMER REQUIREMENTS
IMPORTANCE
HOW
1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20
SERVICE COMPLAINTS
CUSTOMER RATING
WORSE
BETTER
1 2 3 4 5
45 2 5 35 4 8 11 15 12
WHAT
RELATIONSHIP MATRIX
IMPORTANCE
CUSTOMER COMPETITIVE ASSESSMENT
OBJECTIVE TARGET VALUES
HOW MUCH
TECHNICAL COMPETITIVE BENCHMARK
BETTER 5
4
3
2
WORSE 1
ENGINEERING COMPETITIVE ASSESSMENT

FIGURE 13.4.6 QFD—the house of quality.

The second step is to translate the WHATs into HOWs, that is, how the design engineers intend to satisfy the customer requirements. The design requirements are entered in the separate columns of the horizontal HOW block on top of the matrix. The form of the matrix now makes it easy to show which HOWs contribute to achieve which WHATs, the third step in the QFD analysis, by marking the squares created by the corresponding lines and columns. The nature of the relationships—strong, medium, and weak—can be indicated by using different symbols for the markings.

The fourth step in phase 1 is to decide how much of the HOWs we want, that is, the level of the design requirements (e.g., the pulling strength necessary to start a mower). These data are entered in the HOW MUCH horizontal block at the bottom of the matrix.

On top of the matrix is a grid at an angle of 45° to the lines and columns. This makes the whole matrix look like a house, which is why the QFD matrix is also called *the house of quality.* This grid allows us to check whether there are any relations between the different design requirements at all, and if so, if they are supporting or conflicting. The findings can then be entered as symbols in the corresponding squares of the grid.

As a refinement of the matrix, available data on competitors' products can be entered in the WHAT, HOW, and HOW MUCH blocks. Finally, with all the data available in one fairly easy-to-read display, the plans for the product and how to design it can be thoroughly analyzed, discussed, and optimized. Having done that, it is time for the next phases of the QFD analysis.

Phase 2 is the product engineering activity. Here, the engineering requirements from phase 1 enter as the WHATs, and the new HOWs are the part characteristics of the product, determined so as to satisfy the "how much" of the engineering requirements. However, if all characteristics for all parts needed to meet the requirements were to be entered in the matrix, this would soon be too unwieldy to handle. Consequently, one can afford to enter only such parts characteristics that are critical: important, difficult, or new to the design and production organizations. Again, based on the information contained in the matrix, analysis, discussion, and optimization takes place.

In similar fashion, the parts characteristics enter as the WHATs of phase 3, the process planning, where the key processes are determined and shown as the HOWs, with process capabilities as the HOW MUCHs. Once more, before determining the process specifications, all the data is analyzed and discussed and an optimization is attempted. Finally, the process specifications are entered as the WHATs of phase 4, the production planning, where the detailed production requirements are determined as the HOWs of this phase. All four phases of a QFD analysis are shown in Fig. 13.4.7.

The QFD method has several advantages. First, the customer's requirements are systematically pursued through the entire process of developing the product and the production processes. Second, in each phase engineers from the departments concerned are pulled together and act as a team in performing the analysis and optimization, which ensures that all available experience is fully utilized and that the best possible conditions for quality are created. The team approach also ensures buy-in and consequently smooth implementation. As always, the joint analysis and discussion provides an effective learning situation across function borders, and, finally, the filled-in matrices provide an excellent documentation, invaluable for future projects or for problem solving.

Failure Tree Analysis. Failure tree analysis (FTA) is a deductive analysis method for determining the possible causes for the failure of a function in a system, which can be a product or a system of connected products, or a process or a system of interrelated processes. The analysis starts with a failure event, such as the failure of a starter motor to crank the engine (see Fig. 13.4.8). Based on the structure of the system under study, it is determined which components, at the next lower level of the system, could cause the failure event by their failure, and through what failure modes. For each one of these potential failure sources, the same analysis is then performed with regard to the next lower level again, and so on throughout the entire system, until all possible failure sources at all levels have been identified, together with their potential failure modes.

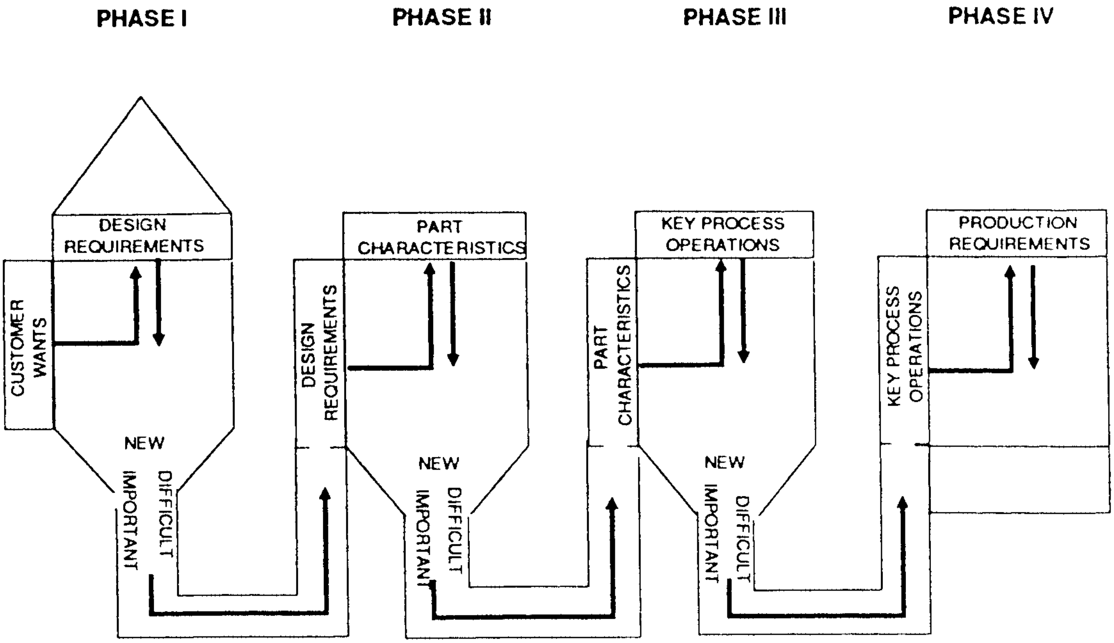

PHASE I
PHASE II
PHASE III
PHASE IV
DESIGN REQUIREMENTS
CUSTOMER WANTS
NEW
IMPORTANT
DIFFICULT
PART CHARACTERISTICS
DESIGN REQUIREMENTS
NEW
IMPORTANT
DIFFICULT
KEY PROCESS OPERATIONS
PART CHARACTERISTICS
NEW
IMPORTANT
DIFFICULT
PRODUCTION REQUIREMENTS
KEY PROCESS OPERATIONS

FIGURE 13.4.7 QFD—the four phases.

In our example, the primary potential cause for the starter failure could be the battery. A battery failure could be caused at the next level by the alternator controller, which could in its turn fail because of a failing transistor. Similar chains of potential failure sources and modes could be identified for other hierarchies of components and parts in the engine-starting system.

The failure tree is a variety of the cause-and-effect diagram, a bit more systematic because it follows the system structure closely, and more specific because it identifies the specific potential failure modes.

Failure Mode and Effect Analysis. Failure mode and effect analysis (FMEA) is an inductive method for identifying potential failures in a system, product, or process, and for determining the consequences of and possible countermeasures against such failures. The method was first developed in the U.S. aerospace industry in the 1950s and has gradually spread to other industries, so that it is now standard procedure for most companies. Although the systematics of FMEA is excellent when used by an individual engineer, the full advantage of the method is exploited only when the analysis is made jointly in a team of knowledgeable and experienced people.

As in the case of the failure tree analysis, FMEA is based on the structure of the system under study. For every part or component of the system—or at least for those parts and components deemed critical enough to study—a list is created of its potential failure modes: all possible ways in which the part or component could fail. When establishing the list, the failure history of similar systems, and the knowledge and experience of the team members, must be utilized fully. In addition, creative thinking and brainstorming should be mobilized, especially for new types of systems, where earlier experience is lacking.

For each system element (subsystem, part, or component) that will be analyzed, a form, or a set of forms, will be filled in, as shown in Fig. 13.4.9. All the failure modes from the already established list are entered in the appropriate column, and for each of these failure modes the team will work through the following steps.

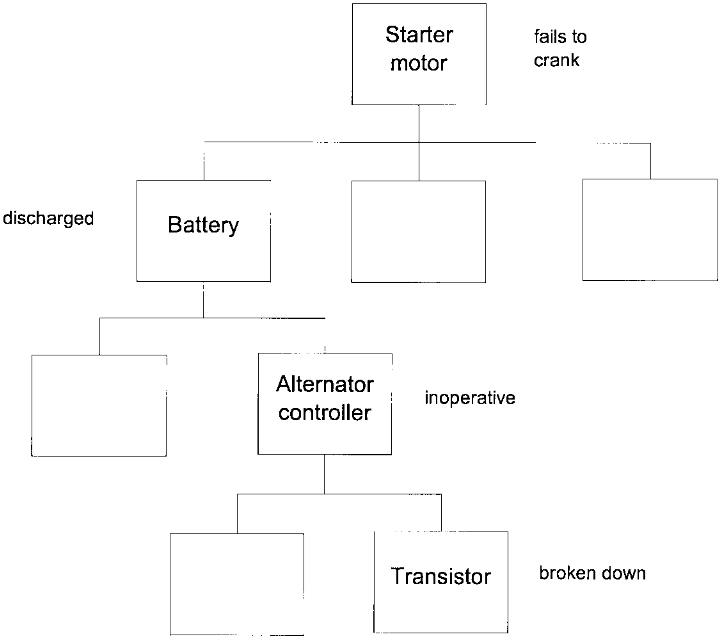


FIGURE 13.4.8 Failure tree.

First, in a process similar to that used when the list of failure modes was established, the possible consequences of each failure are determined and entered in the effect column. Next, using this same process, a countermeasure—a way to prevent the failure from developing or to alleviate its effects—is generated and entered in its position in the form. The same process is again used to determine how the causing problem would be detected should it occur, and this detection measure is entered in its column.

Finally, an evaluation is made of the effect of the factor failure consequences, countermeasures, and detection measures. The seriousness of the failure consequences is evaluated

Part: Alternator controller							
Function: Regulating charge							
Failure mode	Failure effect	Seriousness	Counter measure	Failure probability	Detection measure	Detection probability	Potential failure risk
Transistor breakdown	Battery discharged	10	Parallel circuit	2	100% function check	4	80

FIGURE 13.4.9 FMEA.

on a scale from 10 for very serious, to 1 for trivial. The probability of the failure occurring in spite of the countermeasures is evaluated on a scale from 10 for very high, to 1 for insignificant. Then the probability of detecting the failure is evaluated on a scale from 10 for very low, to 1 for very high. An expression for the risk potential of a specific failure mode is arrived at by multiplying the three numbers, which gives a scale from 1000, indicating extremely high risk, to 1, meaning no risk at all.

The risk potential numbers for all the documented failure modes are used to set priorities when acting on the FMEA results; that is, taking such actions as changing or redesigning a product or process or introducing more stringent quality control. The objective of making the considerable effort of performing an FMEA is risk reduction through failure prevention, by identifying what could cause problems and taking all necessary countermeasures, before any problems have actually occurred. The risk potential number is not to be considered a scientific truth; it is just an assisting indicator.

The important thing about a FMEA is that it is being done jointly in a team, for the increased effectiveness of decision making because of the results of the analysis, and in implementation of the decisions, because of improved buy-in by the team. The documented FMEA itself makes a significant contribution as a medium where specific experience and information about problems and solutions is readily available, for example, to new generations of design or process engineers.

FMEA is a valuable tool to be used in the development of products, processes, and services of all kinds. The earlier in the development process FMEA is used, the better—within limits. It is an advantage to be able to influence a planned product or process before too much has already been invested. On the other hand, the product or process development must be far enough advanced for there to be a visible system to discuss. Ideally, product FMEAs should be made when the engineering requirements are established and again at the prototype stage, while process FMEAs should be made when the processes are being specified and again shortly before start of production. Whether one can afford to do all this, is another question. FMEA is not an end in itself; it is a tool to be used as it fits in the user's situation.

Error-Proofing. Error-proofing or, to use a Japanese name, *poka yoke* is not by itself an analytical method. It has been included in this section because it can be a useful tool when a FMEA has been concluded. It is a method to prevent unintentional mistakes, and it is in principle very simple. All it takes is imagination, to see where these mistakes could occur and to find simple ways of making those mistakes impossible. Figure 13.4.10 shows two very simple examples.

In the first example, a failure can be caused by putting a symmetrical component upside-down in an assembly fixture, and the solution is to make the component unsymmetrical. In the second example, the problem is to choose the proper one from three superficially identical components. A simple solution is to include a notch in the component, located in different positions for the different component varieties, and a feeler pin in the fixture. Both these are examples of positively blocking the opportunity for a mistake. In other situations this may not be possible, and other means must be used, such as sensors built into the equipment to indicate mistakes by signal or by interruption.

These practices are basically standard procedure for most process engineers and many product design engineers. Nonetheless, the method has been mentioned here, very briefly, as an important tool for safeguarding products and processes.

Industrial Engineering Tools

Industrial engineering methods and tools are of course discussed elsewhere in this handbook. However, some of them are used routinely in quality planning and, above all, in quality improvement. These are flowcharting, operation and process analysis, and work simplification.

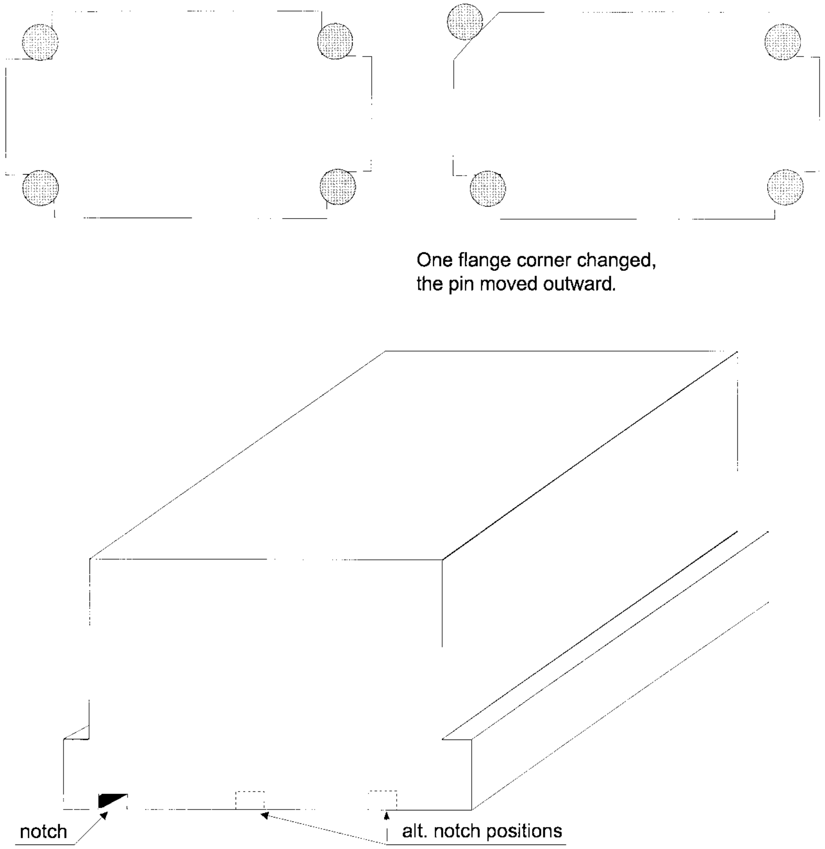


FIGURE 13.4.10 Error-proofing.

Certain other methods and approaches used in industrial and process engineering are also very important to improving and maintaining quality. Cycle time reduction demands consistent quality, while JIT and continuous flow operation (CFM) require practically perfect quality and consequently enforce vigorous quality improvement action. Both approaches also result in a minimum of stock between operations, leading to immediate detection and correction of any failures.

QUALITY INFORMATION COLLECTION

Information, which means data collected, processed, and arranged so that it can be acted on, is the lifeblood of every organization. To manage quality planning, control, and improvement, quality information is required. That means not just information about quality, but information that is of high quality: adequate, correct, specific, and quantified. As the saying promises, "What gets measured, gets done!" The sources of this information are manifold and various, often different for different purposes. To control the quality of the information and its sources is an absolute prerequisite of managing quality.

Internal System Information

The manufacturing processes of a company are usually the largest source of quality information for a company. First, the continuous flow of information is deliberately created to control the products and processes, from inspection and test activities, and direct process controls, whether manual or automated and integrated. Then there is information from periodic investigations, such as capability studies or planned maintenance operations, and from defect investigations, problem-solving activities, and other discrete actions. In nonmanufacturing operations, such as services or administration where no long tradition of inspection or quality control exists, particular attention must be paid to determining what information is needed and how it should be collected.

A company's internal information systems usually also contain external quality information from sources such as customer complaints or warranty data. Information that can be extracted from such sources is especially important because it indicates problems and reactions of the customer, whose satisfaction is crucial to the survival of the company. For customer complaints, a specific complaint management procedure or (in larger organizations) system is necessary. It is needed not just to mollify an annoyed customer for the moment, but also to help solve his or her immediate problem and extract and feed back into the organization useful information about problems and customer reactions.

Warranty data is a potentially rich source of quality information; to fully exploit this potential is an arduous task. For instance, to know that a certain percentage of products sold fail after a period of time in use is interesting, but not enough to do anything about. To be able to act, more specific information is needed about under what circumstances the product failed, what the symptoms were, what part or component of the product failed or seemed to cause the failure, and, ideally, what the root cause was. Very rarely, where the companies' own field representatives make the repairs on-site, is all this information available. In most cases, when the repairs are made by dealers or authorized repair shops, the information does not go beyond what parts failed and possibly what the symptoms were. One way of getting at more specific information and possibly even root causes is to have all failed products returned to the manufacturer for analysis. For obvious cost reasons this is possible only for very special products; a more normal procedure is to have some of the replaced parts or components sent back. For most manufacturers of anything, except strictly customized products, a well-organized warranty information system is necessary, covering everything from problem analysis instructions and input data coding keys for the dealer to statistical analysis and preparation of graphics for quality improvement activities and product development decision making. To develop and implement such a comprehensive system requires the close cooperation of practically all departments of the company.

Customer and User Surveys

For the development and improvement of products, it is crucially important to know what the customers or end users think of a product, and what their needs, requirements, and expectations are regarding the product and its use. For companies with a limited number of individual customers this is simple enough; they must maintain frequent contact with their customers. In other situations, where the number of customers is large or where there is a chain of distributors and dealers between manufacturer and end user, customer or user surveys are necessary to discover the desired information. While the departments of the company that are going to act on the information will want to participate in determining what information will be extracted, it is wise to leave the formulation of the questions to professionals.

To perform the survey and to compile the information is also best left to a professional market research organization. If the survey is done by an independent market research organization, competitors' products used by the company's customers could be included; also other customers of the competitors could be included, provided there is some means of identifying them. Information about the competition of course adds much to the value of the survey results. For certain products (e.g., cars) multibrand surveys are already being done and marketed by independent market research companies. Buying in to these surveys gives a sponsoring company the detailed information about its own products and statistical comparison data about competitors.

Reverse Engineering

To buy a competitor's products in order to study them, to disassemble them and measure and check the components, and to compare them with in-house products is an effective way of gathering information on design methods, materials, and to a degree, manufacturing methods. If applied to larger numbers of a product, an idea of process variations can be developed; applied to larger numbers of used products, reliability and similar data can be estimated. Building up this type of information usually costs time and effort, but the knowledge can be invaluable in a competitive market.

Benchmarking

A benchmark originally was a mark or a series of marks cut into the edge of a workbench to provide a standard for measuring lengths, for example, of cloth. From there it developed to mean the standard for performance, something among the best of its kind, and that is how the term *benchmarking* is used today, signifying a comparison with what is best in its class.

Benchmarking is a way of making competitive comparisons between a company's products, services, and processes and those of the best competitors to establish standards for the company to meet or surpass. It must, however, be emphasized that the benchmarking process itself is not competitive nor clandestine; on the contrary, it is an open, mutually advantageous exchange of information between two partners who have voluntarily chosen to jointly participate in the process. This of course means that the participants cannot normally be direct competitors, at least not with regard to the objects of the comparisons.

Benchmarking the complete design, components, and materials of a company's product with the similar product of a competitor is not realistic because nobody would want to disclose such strategic information to a competitor. On the other hand, two competitors may well be interested in comparing the use of certain more general materials, or of procedures or processes judged not to be of any strategic importance, and so have a basis for benchmarking these.

Generally benchmarking is, however, done by noncompeting companies. The products that can be compared will then be parts or components similar or even identical but used as elements in totally different end products. Manufacturing processes or individual operations can be compared even if they are very similar, as long as they are not used for competing end products. Services and administrative processes can usually be compared freely. It does not matter what business or industry branch the company to be used as a benchmark happens to be in, as long as the processes to be compared are of a similar type. The key to benchmarking is the mutual interest; there must be something for both partners to gain.

Benchmarking starts by a company deciding what, perhaps a specific process, to benchmark. This is the critical decision that determines all following steps and should be very well prepared. The next step is to determine which other company is best in class with regard to this type of process, and to determine what type of information is desired and how the information could be collected. Then contact is arranged with the other company through appropriate channels, and a meeting is sought, to try to establish a mutual interest. If this succeeds, a joint plan is put together, including programs for site visits and procedures for information collection and analysis. Then the visits take place; the information is collected and processed, and a joint report is put together about the study and its results.

Based on the findings, each of the participating companies makes its analysis, determining any substantial differences in performance and consequent improvement needs, setting targets for these improvements, and putting together specific action plans for their realization. Action is taken, the results are monitored, and corrective action taken as needed. When results are satisfactory, new benchmarking projects may be contemplated.

QUALITY PLANNING

Quality planning includes the activities necessary to define and specify the intended quality of the product or service, as well as the consequential requirements on product design, process design and manufacturing engineering, process control, and product inspection and testing. The quality planning activities must be integrated as a part of the process of planning, developing, and engineering the products and production processes.

Quality Objectives

For all nontrivial product characteristics—in categories such as performance of various kinds of functions, safety, reliability, durability, serviceability, environmental protection, fit and finish, and noise—quality objectives or standards must be determined. This is done in conjunction with the product planning process and based on all available information about competitors' and in-house products, from market research, customer surveys, product comparisons, and benchmarking, as well as on internal information on present quality levels of existing in-house products. These objectives are normally defined at end product or system level and need to be deployed to the lower levels of subsystem, part, or component to make them suitable for action. They are brought into the planning process in the phases for product planning and product engineering, respectively.

Quality objectives and standards for the production processes are determined based on the detailed product quality objectives, compared with performance data from existing processes, capability data for planned new processes, and benchmarking information. They are brought into the planning process in the process planning and the production planning phases, respectively.

Product Planning and Engineering

To develop a new product and put it into production is one of the most important processes of the company, the success of which can be crucial to its survival. To ensure the success, all pertinent knowledge and experience in the company must be fully exploited, which means that many of the company's departments must actively participate in the process. At the same time, the responsibility for the several phases of the process must be clearly defined.

For the first two phases, product planning and product development and engineering, the departments involved with product planning, marketing, product engineering, process planning and manufacturing engineering, production, quality assurance, and product and customer service—or the organizational units with these functions—should participate. Representatives of these departments form a team, with joint responsibility for the outcome of the planning process. Responsibility for managing the process could be given to a project manager, but a special responsibility for the first phase rests with product planning or marketing, and for the second phase with product engineering as responsible for the actual development of the product. The other team members provide information, contribute their experience, and look after their functional interests.

For both these phases, quality function development (QFD) should be used as an instrument for coordination and documentation of the results.

In the actual product development activity, teams with specialists from process planning and manufacturing engineering, production, quality assurance, and product service should support product engineering in performing failure mode and effect analyses (FMEAs).

Process and Production Planning

For the next two phases, process planning and production planning, basically the same team—although now reduced to the representatives of product engineering, process planning and manufacturing engineering, production, and quality assurance—continues the planning process in similar fashion as for the two first phases. The project manager could be the same as before, but the special phase responsibility rests with process planning and manufacturing engineering and with production, respectively. This does not in any way encroach on the various functional responsibilities, such as quality assurance's responsibility for quality standards or inspection planning.

Also for these two phases, quality function deployment should be applied, at least for critical processes and operations or where new methods are going to be implemented. Furthermore, for all critical or more important ones, and definitely for all new or radically changed operations or processes, failure mode and effect analyses should be performed.

QUALITY CONTROL

Quality control includes all activities necessary to make sure that products meet all requirements and that processes meet their specifications. Quality control can be thought of as composed of three separate activities: first, to measure and evaluate the characteristics of a product or the performance of a process, second, to compare the results to specifications and determine any discrepancies, and third, to act on the discrepancies.

Inspection and Test

The activities through which the characteristics of a product are checked, examined, measured, or tested and evaluated for conformance to standards and specifications are designated as inspection. Testing is used to characterize checking or measuring product function or performance. The performance of a process can be checked in two ways, either direct by measuring process variables, which would be characterized as process monitoring, or indirectly by checking samples of products taken from the process, which would then again be designated as inspection, although for process control purposes.

Inspection can be characterized according to how it is being done, either as manual or as mechanized or automated. It can also be characterized by its extent—by the proportion of a population that is being inspected—as sampling inspection or as 100 percent inspection. Sampling inspection is done to determine the performance of a process, or the quality level (such as the proportion defectives) of a batch of products. Statistical sampling methods for acceptance inspection have been used extensively for receiving inspection of materials or components from outside suppliers. This practice has almost disappeared because suppliers are required to ensure their quality in the first place, and the number of possible defectives should be so low that no sampling inspection would expect to catch them. It can therefore safely be said that sampling inspection in industry today is used solely to control process performance.

One hundred percent inspection is used where no other method is feasible because of the complexity or sensitivity of the product, for example, for function testing or finish inspection at buy-off points or at final inspection before shipping to customers. In another, very different situation it can be necessary to fall back on 100 percent inspection, which would then be characterized as sorting. If a process temporarily runs out of control, sorting of the produced parts must be established immediately and maintained until the process is back to normal. Sorting must be permanently instituted for processes that are inherently incapable of meeting specifications.

Humans are not very good inspection instruments, with an accuracy of between 50 and 90 percent, depending on circumstances. Consequently, whenever sorting or 100 percent inspection must be used, every effort should be made to mechanize or automate the inspection operation.

Inspection activities are performed at different points in the production chain. Parts and supplies from outside suppliers are subjected to receiving inspection, which today is usually just an identification control; only in exceptional cases are parts truly inspected. In-process inspection is performed to control manufacturing operations and processes, intermediate buy-off inspection and testing is done for subassemblies, and final inspection and testing of the completed end products is conducted for buy-off to shipping.

Process Control

Continuous processes and highly mechanized operations are usually designed to continuously monitor their performance and make corrections for any discrepancies; process control is integrated. In all other cases, process control is periodic, either by intermittent monitoring of process variables, or by taking samples of products from the process and inspecting them, and making corrections to the process whenever the results indicate that the process is out of control.

Statistical process control (SPC) is presented in-depth elsewhere in this handbook; nonetheless, some aspects of it will be discussed here. The first prerequisite for use of SPC is that the process in question is stable, that is, behaving according to a definite pattern, which makes it predictable. It is then said to be in statistical control, within its pattern. The second prerequisite is that the process also is capable of producing products, which conform to specifications. This means that the process capability is at the very least equal to 1. Most companies today insist on a capability of 1.33 or better, some demand as much as 3.0.

Given a process known to be stable and capable, SPC means to monitor its performance with the help of a control chart and to leave it alone, as long as the chart indicates that the process is behaving normally, and adjusting it only if it exceeds established limits. This is depicted in Fig. 13.4.11.

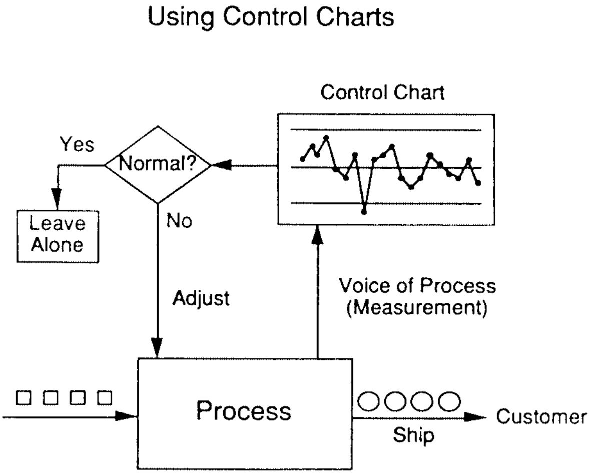


FIGURE 13.4.11 Process control.

The whole process, leading up to establishing statistical process control for a process, is shown in Fig. 13.4.12.

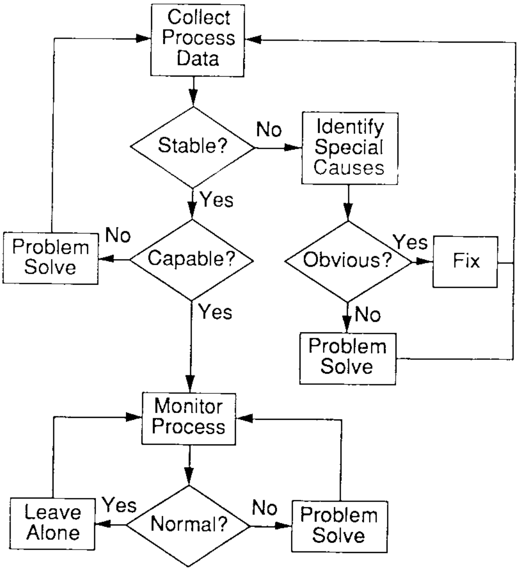


FIGURE 13.4.12 Establishing process control.

Auditing

The effectiveness of the quality control activities requires monitoring, which can be done at several levels by auditing. An audit is an examination of a subject using a predetermined list of objects to check and standards that must be met against which the performance of the subject is evaluated. The most frequent form is the product audit, where a sample of products is taken at regular intervals and checked against a checklist comprising a number of characteristics of greater importance, usually from the point of view of the customer. The results of product audits performed regularly give a picture of the product quality and its development over time, as well as a measure of the effectiveness of the quality control system. Similarly, processes such as an assembly operation can be monitored to evaluate the effectiveness of the process control.

The current interest in systems audits has been caused by the trend towards certification to ISO 9000 and other standards. Systems audits have, however, been used internally since the early 1970s, as a way of monitoring how closely documented systems and procedures are being adhered to and of determining the need for change or improvement of them.

Quality Control Organization

A complete list of quality control or quality assurance functions would comprise administration, quality engineering, supplier quality assurance, receiving inspection, measuring room and laboratories, in-process inspection, interprocess inspection and buy-off, final inspection and buy-off, product audit, and systems audit. In the 1970s, all these functions would typically be assembled into one central organization, quality assurance. This centralization of responsibility no longer fits in today's organizational landscape where striving for cooperation and involvement calls for integration of responsibility and of functions.

Today, in-process inspection would typically be integrated in the processes or replaced by operator control. Interprocess inspection and buy-off would very often be integrated in the operations, as would sometimes even the final inspection and buy-off. Quality assurance would consequently, in most cases, be responsible for final inspection, and for all the remaining functions listed previously.

In order to clarify what this means, two of the functions in the list should be explained. *Quality administration* covers quality systems and procedures, quality cost analysis, and the internal administration for quality assurance. *Quality engineering* usually comprises all or most of the functions of quality planning, inspection planning, failure analysis, quality information analysis, warranty data analysis, and reliability analysis.

QUALITY IMPROVEMENT

Quality improvement includes the activities necessary to identify improvement needs and opportunities, to define and implement improvement actions, and to verify their effectiveness. The customers' quality expectations keep increasing and competition keeps improving, so unless a company constantly keeps improving its quality, it will eventually be forced out of the market. This makes quality improvement an absolute imperative in the somewhat longer-term perspective, while simultaneously being profitable short term in many cases.

Continuous Quality Improvement

Continuous improvement builds on the presumption that there are opportunities for improvement everywhere, and that everybody in an organization can make some contribution to improvement given the necessary favorable conditions—training in using suitable tools and methods, and freedom and encouragement to participate. There is a rich source in every company to be tapped by continuous improvement; on the other hand, constant improvement is needed also to compensate for the deterioration occurring in any system left to itself, and to preserve any gains.

Continuous improvement is best implemented by encouraging formation of improvement teams in groups of coworkers of the normal working organization. This will, however, not happen spontaneously; on the contrary, a carefully planned, implemented, and maintained process is necessary. It starts with a number of companywide interactive training sessions where the concept of continuous improvement, its methods and tools, and the proposed involvement of the employees in the process are described, explained, and discussed with the participants.

The next step would be to identify a few groups of employees, interested enough to accept acting as bellwether teams, to constitute the teams and to give the team members some initial training. They would then, maybe with some leadership, chose an improvement project and start their improvement work, layered with further training and supported by a coach as needed. The training should make the team members able to use some of the tools described previously. The training would start with the seven basic tools, some very basic statistics, and interactive problem solving. Later, as needed during the project, some operation analysis, SPC, and error-proofing could be added.

Once positive results from the bellwether teams begin to appear, these results, how they were achieved, and the experience of the team members should be publicized extensively but correctly, to create interest in the organization and encourage formation of new teams. A reward and recognition program should be installed, with recognition given publicly to successful teams. A publicity program should be put in place to regularly inform about training programs, team formation, methods successfully applied by the teams, and results—both for individual teams and the company.

Managers and supervisors must be involved in planning and implementing the process, in order to accept and support it. They should also be given a certain amount of training in the methods used, more than the initial companywide sessions can provide, to enable them to support their employees in the projects. Ideally they should also form improvement teams at their own levels.

The continuous quality improvement process needs a supporting organization. First, there must be visible support at top management level by a champion and sponsor. Second, a coordinator or coordinating group is necessary to manage what administration and support is needed, as well as the activity reporting and publicity. Third, training and trainers, and facilitators and coaches, must be available when needed. Finally, the support of the first-line supervisors is crucially important.

Project-Oriented Improvement and Breakthrough

Quality improvement in a company must by necessity be two-pronged, one prong for the more spontaneous, one-small-step-at-a-time continuous quality improvement process. The other is the strictly target-oriented and more structured process required to make quality shift to new and much higher levels—that is, to achieve what Juran has described as *breakthrough.*

A need for breakthrough may arise, more or less suddenly, caused by changes in the market, new product development by competitors, or development of new technologies. The need can also develop gradually, as a competitor successfully implements an improvement program, or even creepingly, caused by in-house neglect. On the other hand, opportunities for major improvement also may arise, driven by the availability of new technology or, in-house, by a planned new generation of products or a planned new manufacturing plant.

Information about quality improvement needs and opportunities may originate in or be picked up by almost any one of the company's departments, but needs to be collected and consolidated in one place, usually in the quality planning function of quality assurance. Quality assurance will include this information in its quality reports. However, to get improvement action, the company must organize itself for it.

The first step is to recognize quality as a top management responsibility, by establishing the company's quality council as a forum for reporting on quality, deciding on quality improvement actions, and assigning resources for these actions. Members should be the president of the company as chairman, the heads of finance, marketing, engineering, production, and quality assurance; the latter would also be responsible for the administration of the council. The quality council would convene periodically, two to six times per year.

At the meetings, quality assurance would report on quality status, needs, and opportunities for improvement. The council would determine priorities, decide on action to be taken, and projects to be started. It would also appoint team leaders for the projects and assign resources as needed. Team leaders for ongoing projects would report on project plans and status, and on support needed for the council's decision.

An improvement project team is formed by knowledgeable and experienced representatives of the functions or departments concerned. The team members are given training in interactive problem solving and in other methods and tools, to the extent required and at the time when it is needed in the progress of the project. There are many similarities between working in an improvement project team and a team for continuous improvement but also major differences—most important, that a project is specified by management and limited by time.

FURTHER READING

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BIOGRAPHY

Per A. Sörensson has been an independent consultant since 1994, specializing in quality management and quality management training. Prior to that, he spent 35 years in production and quality management in the automotive industry in Sweden, Germany, and the United States, and held positions as vice president for quality assurance for Volvo in Sweden and for Volkswagen in the United States. He holds an M.Sc. in mechanical engineering from Chalmers University of Technology in Gothenburg, Sweden, and an M.B.A. from CEI in Geneva, Switzerland. He is a senior member of American Society for Quality (ASQ) and European Organization for Quality (EOQ) and an academician in the International Academy for Quality.

CHAPTER 13.5

COMPLYING WITH ISO 9000

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The ISO 9000 Quality System Standards were originally published in 1987 and have become widely accepted in industrialized nations. The standards define requirements for documenting marketing, design, manufacturing, and servicing processes to achieve operating consistency and increased credibility with customers. If a company wishes to be certified to these standards it must undergo recurring audits by external agencies called registrars. Preparations for the initial audit, which hopefully leads to certification, usually take from 12 to 18 months. This chapter will discuss selected ISO 9000 subjects where a practical approach may ease the task of preparing for certification.

INTRODUCTION

The ISO 9000 Standards require documented procedures and records for marketing, design, manufacturing, and servicing processes. The key test of compliance with the standards is a comparison of procedures with actual tasks being performed. A procedure and the actual task must be identical to ensure consistent execution of formal documented instructions.

The ISO 9000 series consists of several detailed standards. ISO 9000 itself serves as a general guide to the use of specific standards. If a company has a product design function, it must be certified to ISO 9001, which contains 20 elements including the element for design control. Concerns that manufacture another company's design are certified to ISO 9002, which does not contain the design control element. ISO 9003 is used primarily by testing laboratories that neither design nor manufacture a product. There are a number of other 9000 series standards that essentially interpret and add details to 9001, 9002, and 9003. The publications listed at the end of this chapter cover the complete ISO 9000 series and related information. This chapter discusses certain ISO elements and other subjects that may ease the task of preparing for certification.

Even though compliance with ISO 9000 implies a positive effect on product quality, this is not necessarily so; product quality itself is not subject to audits by registrars. Thus, the ISO 9000 Quality System Standards are but a part of total quality management (TQM).

Many companies now require that their major vendors be ISO 9000 certified to have some assurance that the vendor operates in a controlled environment. Chrysler, Ford, and General Motors have gone a step further; they have issued standards based on the ISO 9000 series with additional requirements for the automotive industry, known as QS 9000. Their first-tier suppliers are required to be certified to this standard.

The industrial engineer's role in preparation for and compliance with ISO 9000 consists of developing and issuing documented instructions to be followed on the manufacturing floor, to revise such instructions promptly to reflect updated methods, and to work with floor personnel to make sure that instructions and actual tasks are identical.

ORGANIZATION TO PREPARE FOR ISO CERTIFICATION

The effort begins when senior management decides that ISO 9000 certification is a desirable and possibly necessary requirement to standardize internal practices and maintain market share. The first step should be the appointment of a coordinator who becomes responsible for preparing the company for the registration audit, including training of all employees. The coordinator should be a respected management employee whose past performance has shown timely achievement of project objectives even though the person may not be the direct supervisor of people who participate in the project. There may be a slight advantage to choosing a member of the Quality Assurance Department, but of far more importance is the coordinator's ability to achieve results working with almost all departments in the organization. The coordinator should report to the senior management person responsible for quality.

Many ISO 9000 articles and books recommend that a management steering committee be formed to guide the coordinator. This author believes that the roles are actually reversed. The coordinator will act as an instructor for such a management group, keeping them informed of progress and training them with respect to ISO requirements. The only "steering" function of the committee is the approval of the coordinator's project plan and associated expenditures.

Before starting the assignment, the coordinator should attend a training course covering ISO fundamentals as well as a course on auditing. It may be advantageous to hire a consultant for a period of time but this is not a necessity. Typically help is available from local chapters or from acquaintances whose company has already achieved ISO 9000 certification. The key to successful preparation for the ISO registration audit is the ability and personality of the coordinator, so choose that person with great care.

TRAINING OF EMPLOYEES

Management, technical, and office employees should receive basic ISO training conducted by the coordinator soon after the project has been started. Subjects can be covered in about four hours, possibly split into two-hour sessions to keep the audience's attention. It is best to stay away from a detailed explanation of each of the ISO elements (20 for ISO 9001). In the course of preparation for the registration audit, employees will gradually absorb the detailed meaning of each element that affects them. Rather, these basic training sessions should cover the history of ISO 9000, its spread to all industrialized countries around the globe, and reasons for seeking certification. The need for documentation that always reflects current practices should be stressed; up-to-date documentation is the backbone of ISO. The requirement for external and internal audits should be covered, with special emphasis that these recur at regular intervals, thus ensuring that compliance with the ISO requirements continues unabated. The audience will want to know how long it will take to get ready for the registration audit conducted by the chosen registrar. The coordinator should explain that the critical project path is essentially the sum of the time required to prepare and control documentation, plus the time required to audit internally each of the ISO elements at least once prior to the registrar's visit. The typical time span is from 12 to 18 months. Basic training should also cover registrars, assessors, and their common practices when auditing a facility. This subject is discussed in more detail in the subsequent section, Registrars and Assessors.

Basic training for shop employees should be conducted much later, within four to eight weeks prior to the registration audit. Classes ought to be limited to 25 people and should last a maximum of two hours. It is best to conduct training near the beginning rather than the end of a shift to hold the participants' attention. Introductory subjects cover a short history of ISO 9000 and the company's reasons for seeking certification. The main emphasis should be on subjects directly affecting shop employees. These include the requirement that work instructions *always* reflect the latest practices, the need for using only calibrated measuring instruments, the requirement for documented status of each shop order, identification of all material, and proper separation of acceptable and rejected material. The closing subject should cover proper interaction with the registrar's assessors.

THE QUALITY MANUAL AND QUALITY POLICY

One of the first tasks is to prepare a quality manual, which has to be submitted to the registrar prior to the registration audit. The manual should include the following sections:

- A table of contents, with each entry showing its effective date. The table of contents should be approved and dated at the bottom of the page by the senior executive of the facility. Make sure that the date is identical to the latest date shown for any of the entries in the table of contents.
- A foreword, which includes a brief description of the products and services provided by the facility, and a statement that the contents of the quality manual will be reviewed once every X years by a specific person, usually the ISO management representative. A reasonable time period between reviews is three years.
- The quality policy. This should be a short concise statement that the company is committed to produce high-quality products and services with on-time deliveries, to achieve total customer satisfaction, and to strive for continuous improvement.
- A short statement signifying management commitment to maintain the quality system. This should be signed and dated by the highest ranking executive of the facility, and preferably, in addition, by the senior executives of each major department.
- The main section of the quality manual repeats each of the ISO elements, customized for the particular facility. This section is easy to write—use the ISO 9001 or 9002 wording as a basis and make whatever minor changes are appropriate for the facility. Example: Section 4.1.2.2 in ISO 9001 and 9002-1994 states:

> The supplier shall identify resource requirements and provide adequate resources, including the assignment of trained personnel (see 4.18), for management, performance of work, and verification activities including internal quality audits.

This might be restated in the quality manual as follows:

> Company ABC has identified and provides adequate resources, including properly trained personnel, for all activities, including internal quality audits.

The key is to be brief and still cover the requirements stated in the ISO Standard. The numbering of each section should be identical to that used in the ISO Standard. In the case of ISO 9002, Section 4.4—Design Control should state that Company ABC does not perform design functions. (If you do design product then ISO 9001 is applicable.) Typically each element can be covered on a single page, with the possible exception of Purchasing (section 4.6), and Control of Inspection, Measuring, and Test Equipment (section 4.11). These may require two pages.

- An appendix containing the basic top-level organization chart. Do not include lower-level charts nor names of incumbents.

Note that the ISO Standards are expressed in the form "the supplier *shall.*" Do not use *shall* or *will* in your quality manual. Use only the present tense, indicating that you are presently complying with the ISO requirements.

Upon completion of the quality manual, a copy should be submitted to the chosen registrar. If the registrar recommends changes, make these and resubmit. The quality manual must be approved by the registrar prior to his registration audit.

DOCUMENTATION STRUCTURING

The documentation structure of ISO 9000 usually consists of four levels. Level one is the quality manual. Level two consists of procedures that define departmental activities: the *who, what, and when.* Level three comprises detailed work instructions that describe in detail *how* an activity is to be performed. Forms and records used in the quality system are level four.

In some instances, a document may serve as both a level two and a level three. Detailed shop floor work instructions are true level threes. It is important to define a document as level two or level three because an index of all procedures and work instructions must be prepared, which should show the relationship of a level three to a higher level two.

Procedure and work instruction subheadings are a controversial subject. Many ISO 9000 treatises recommend that such documents have subsections entitled Purpose, Scope, References, Definitions, Responsibilities, Procedure, and Records. This may be a classically correct approach. However, ask yourself how procedures and work instructions are used. Experienced employees will use them as references and reminders how to do a job, and as training assists when showing a new employee how the job is to be performed. The new employee should refer to these documents frequently while receiving verbal training from an experienced person. As the new employee becomes more proficient he or she will refer to the document less and less, until using it only as an occasional reference. In this author's experience, people want to read a procedure or work instruction that simply lists, in sequence, the steps to be taken. Properly written, such a document contains in its series of steps its scope, any applicable references, definitions, and responsibilities, as well as related records. Furthermore, a properly chosen title of the document defines its purpose. Thus, a simplified approach to preparing procedures and work instructions is to choose a good descriptive title, followed by clearly written sequential steps required to perform the task.

Generally, the degree of detail in a procedure or work instruction is inversely proportional to the education, training, and experience required for the position. For example, detailed work instructions about how to manufacture fixtures to be built by a tool and die maker are not required. The job description for a tool and die maker requires completion of a four-year apprenticeship program and journeyman's papers.

Detailed work instructions should be prepared by or based on input by experienced operators or trainers who usually know more about a specific operation than anybody else. The instructions should then be reviewed by supervision and/or appropriate staff specialists. Try to avoid appendices to procedures or work instructions. If unavoidable, number the appendix pages as a continuation of the procedure itself. This aids proper document control.

DOCUMENT CONTROL

This ISO element is near the top of ISO elements not properly complied with, as evidenced by nonconformities found by internal auditors and registrars' assessors. Much has been written about the subject and this chapter is not intended to discuss basic issues. There are, however, several aspects of document control that bear further discussion.

It is particularly important to have proper control over the issue of procedures and work instructions. In small organizations there should be one central document control desk whose incumbent keeps a constantly updated list of all procedures and instructions, properly indexed, showing the latest revision by date or revision number or both. No other function or person should be permitted to issue such documentation without going through the Document Controller. The document control desk function needs to have an approved distribution list for each document so that revisions can be sent to the proper recipients.

The question often arises how to ensure that users of a document do not inadvertently use a superseded version. A rigorous control system requires that the recipient sign a transmittal form to be returned to the controller, indicating that the recipient has indeed received the latest version. In addition, the recipient must attach the superseded copy of the document, which is then destroyed by the document controller. This system requires a good deal of follow-up activity by the document controller and tends to be somewhat cumbersome. A simpler method involves no more than a transmittal form that does not have to be returned by the recipient, reminding that person to destroy the superseded version of the document. Proper internal auditing can go a long way to achieve compliance. For various reasons a recipient may find it necessary to maintain superseded versions of certain documents for reference. All the recipient has to do is to identify the superseded document with an appropriately worded stamp (such as Superseded Document—Use Only For Reference) and file it. This may be quite appropriate in design, manufacturing, and industrial engineering departments where quick access to previous versions of a document speeds decision making. The document controller must maintain one copy of each superseded document in a file, all such copies properly identified as having been superseded. This represents a history of each such document sometimes requested by preparers or users for a variety of reasons.

In large organizations it may be necessary to have more than a single document controller. Metallurgy may have its own controller, as well as design engineering, manufacturing engineering, and industrial engineering. This is perfectly acceptable, but an effort should be made by the ISO coordinator to have all controllers use a common data system and control method.

A point often overlooked is the requirement to exercise proper document control over externally generated procedures and instructions. Externally generated documents are those issued by industry associations and governmental bodies with which a manufacturer must or volunteers to comply, such as the American Society of Mechanical Engineers (ASME), API, or building codes. The document controller should maintain a hard copy of the latest, as well as superseded, versions of such documents. Let us assume that the latest issue of a specific code is November 1996. Let us further assume that the manufacturer normally complies with a previous version, dated October 1994. Customers should be informed in writing during contract negotiations that the manufacturer will comply with the October 1994 version *unless* the customer insists on the November 1996 version. Final agreement between the manufacturer and the customer should be documented and properly filed by the manufacturer.

A final point regarding document control. It is often necessary to make immediate changes to a procedure or work instruction to overcome problems and continue production activities. In that case, a supervisor may mark up the hard copy of the document being used on the floor, *as long as the supervisor signs and dates the manual notation.* In addition, the supervisor should indicate on the hard copy the time period during which his or her handwritten note is to be effective. At the end of that period, either the official temporarily superseded document again becomes effective, or a properly revised controlled document has been issued. Even with the best document control systems, one can usually see handwritten notices on machinery or bulletin boards that are essentially a type of work instruction. Such notices may, for instance, indicate a special step required when setting up a specific machine tool in a group of identical machine tools that is not dealt with in the official work instruction. It is acceptable to have supervisors post such notices, if they sign and date them and indicate the effective period. In such cases, it is the supervisor's responsibility to maintain in his or her office a log of such notices and their locations to maintain proper document control.

CONTROL OF MEASURING AND TEST EQUIPMENT

There are no exceptions to the requirement that measuring and test equipment in use must be calibrated at regular intervals. Often overlooked is the need to treat employee-owned equipment in the same manner as company-owned equipment. If an employee does not wish to have an owned micrometer checked by the company's calibration laboratory, then the employee should be told to leave the instrument at home.

A common error with calibration records is the absence of noting the amount by which an instrument had to be adjusted to bring it back to proper calibration. Instruments to be calibrated should first be checked to determine whether adjustment is needed and how much adjustment has to be made. This information must be shown on the calibration record. If adjustment is needed, a determination must be made as to what action to take with respect to product that may have passed inspection performed with an instrument out of adjustment. Let us assume that the calibration interval for the instrument is three months. In the worst case, the instrument may have been dropped one day after the previous calibration, resulting in an out-of-adjustment condition for almost three months. As a result, all product checked with this instrument during the previous three months is suspect. An assessment must be made *and recorded* by qualified personnel as to what, if any, action to take regarding such product. In many cases, the product has long been shipped and cannot be traced, and possibly no action can be taken. Such decisions should be recorded. In other cases, product may still be on the premises and can therefore be reinspected and passed, reworked, or scrapped.

Another frequently observed problem is the use of measuring instruments whose resolution is not small enough to check a dimension and its associated tolerance. Instrument resolution is the smallest measurement increment that can be read without visual interpolation between two distinct marks on the measurement scale. Commonly accepted machine shop practice requires instrument resolution that is 10 percent of the tolerance to be measured.

THE ISO 9000 TRAINING CLAUSE

The ISO 9001 and 9002 training clause, 4.18, is short and deceptively simple:

> The supplier shall establish and maintain documented procedures for identifying training needs and provide for training of all personnel performing activities affecting quality. Personnel performing specific assigned tasks shall be qualified on the basis of appropriate education, training, and/or experience, as required. Appropriate records of training shall be maintained.

Appropriate training is the fourth step in a sequence. The first step is development of job descriptions that clearly list the education, skill, knowledge, and experience requirements for all positions in the company. The second step is an evaluation of each employee comparing the employee's education, skill, knowledge, experience, and performance with the requirements listed in the job description. The third step is to determine specific areas in which the employee does not meet the job description criteria and to plan appropriate training. This should be done by the supervisor. The fourth step is to provide such training for the employee. Each of these steps must be documented. Most job descriptions are not detailed enough to serve as a basis for this process. It is often advisable to have a member of the human resources department meet with each supervisor to review and revise existing job descriptions until they meet the requirements. Supervisors should review employees on a regular basis to determine whether training plans have been carried out and what additional training needs may have become apparent since the previous review. Performance review forms should provide space for such comments.

There are, of course, exceptions to the rule that job descriptions show all requirements for a position. For example, a well-written job description was issued in October 1994. The requirements for the position have not changed, but in 1996 the company decided that employees should receive training in total quality management (TQM). There is no need to revise the job description, but records showing training plans and completed training should list the TQM seminars.

A qualification and training record for each employee should be kept by the supervisor.

INTERNAL AUDITS

ISO requires continuous internal audits to ensure that compliance with ISO requirements is maintained. In most cases, a number of employees are chosen from a list of volunteers to be trained and then to conduct such audits. The roster of internal auditors should include shop personnel. Training can be obtained through attendance at external seminars conducted by experienced instructors. Typically, members of the quality assurance department become lead auditors who coordinate audits and guide the auditors chosen from other departments. Obviously auditors should never audit their own department to preserve impartiality. An annual audit plan must be prepared. This is essentially a schedule showing the ISO elements and departments to be audited during each week or month of the year. The plan should take into account the relative importance of each ISO element so that certain elements such as Document and Data Control may be audited several times a year while Customer Supplied Product may be subject to only one audit per year. Such audit plans should have blanks to be filled in with the date of the actual audits. Often the first attempt at creating an audit plan may require revisions after gaining experience. A record file for each audit should contain the handwritten notes made by the auditors during the actual audit, the final audit report prepared after the audit, a copy of nonconformities issued to department managers or supervisors, their responses as to the corrective action they will take and its projected completion date, and a record showing that the effectiveness of the corrective action has been checked by an auditor. This last step closes the loop.

QUALITY RECORDS

Various quality records must be maintained to demonstrate the effectiveness of the quality system and compliance with ISO requirements. As a minimum, records must be kept in each instance where a sentence in the ISO Standard ends with the notation "(see 4.16)." Common sense will dictate additional records that the company wishes to maintain. A list of record types should be kept showing minimum required retention times for each. In many organizations records are maintained in typical office files or on computerized records for a period of time and are then moved to archives. If this is the case, both office and archive retention periods should be shown.

REGISTRARS AND ASSESSORS

Most registrars prefer that their employees who audit companies be known as *assessors,* while persons performing internal company audits are generally known as *auditors.* ISO 9000 requirements are written in a form that requires interpretation. This is no different from the laws of the land that are constantly interpreted by the courts. In the case of ISO 9000, it leads to the question whether all registrars interpret the ISO requirements the same way. Over the years precedents have been set, and in general, there is evidence that registrars are rather consistent in their interpretations. A company seeking certification should recognize that this is not a perfect world and that there may be some differences in interpretation between registrars. Furthermore, the assessors encounter different and sometimes new situations when auditing a company. Thus, two assessors from the same registrar auditing a specific area of a company at different times may not necessarily have identical viewpoints. The company may ask an assessor for a check with his or her home office if company personnel disagree with the assessor's viewpoint. This should be done only in unusual cases.

Occasionally an assessor's personality and behavior leads to frustration and anger by company personnel. The company should not hesitate to contact the registrar's home office and request that the assessor not be a member of the registrar's auditing team in the future. Most registrars will accommodate such a request.

Registrar audits as well as internal audits almost always result in the issuance of some nonconformities. With the best of intentions it is practically impossible to comply with *all* ISO requirements in all locations at all times. Nonconformities should not be the cause of despair but rather the impetus to correct and improve.

In preparation for visits by assessors, a company should provide a room that can be used by them as their home base while on the premises. Assessors should be provided with hard copies of procedures and work instructions in loose-leaf notebooks that contain an index including the latest revision date and/or revision numbers. Assessors should always be accompanied by a company guide who can answer questions and help an employee overcome nervousness when an assessor questions the employee. The guide may well be the department manager or supervisor. The ISO management representative should actively participate in these registrar audits. Assessors rightfully do not like to be accompanied by an entourage of company people, so try to keep the number to no more than two, or possibly three.

Training sessions for company employees should include a few basic guidelines for what to do and not do when being visited by an assessor. First and foremost: *always tell the truth as you know it.* If you don't know the answer to a question, say so. Never lie, or try to evade answering. A truthful answer may result in a nonconformity, but as mentioned before, nonconformities should be considered as opportunities to correct and improve. A lie or evasive answer will only result in the assessor delving deeper into the subject. Second: *answer the questions and be brief.* Some people enjoy hearing themselves talk and tend to continue discussing the subject, then veer off into related subjects. Sooner or later they may disclose a situation that results in a nonconformity even though the assessor had no plans to ask that particular question. Third: *keep your work area neat and clean.* An assessor knows that a cluttered and dirty workplace is more likely to disclose nonconformities than an orderly one.

A FINAL OBSERVATION

The effort required to achieve ISO certification and practice continuous improvement is substantial, both in cost and time. These negatives are offset by the fact the ISO 9000 Quality System Standards are an excellent taskmaster leading to consistency in a company's operations, ideally resulting in improved product quality and customer satisfaction.

FURTHER READING

Peach, Robert W., and Diane S. Ritter, *The Memory Jogger™ 9000.* (pocket guide)
Sanders, Donald A., *Passing Your ISO 9000/QS 9000 Audit.* (book)
Voehl, Frank, Peter Jackson, and David Ashton, *ISO 9000, An Implementation Guide for Small to Mid-sized Businesses.* (book)

BIOGRAPHY

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CHAPTER 13.6

THE ROLE OF STATISTICAL PROCESS CONTROL IN IMPROVING QUALITY

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Conventional SQC was originally positioned as a management technique that experts used to solve special quality problems. Because technical knowledge was necessary for setting the conditions and because the calculations were complicated, the technique was regarded as difficult for amateurs to handle. Today, however, in spite of the fact that conditions surrounding quality problems have become even more complicated, quick response and precise decision making are required. This in turn demands that SQC be used more widely. Fortunately, much progress has been made in the areas of standardization and computerization of the various techniques for solving quality problems. No longer burdened by complicated calculations, practitioners can now adopt SQC techniques for use in real time. As a result, traditional Statistical Quality Control is being applied to production processes, and wide use of SPC has become possible. These advances have enabled companies to seek major innovations in manufacturing. In this chapter, the process through which SQC has been developed will be reviewed and the practical application of SPC will be explained through several actual examples.

TQC, TQM, AND SQC (STATISTICAL QUALITY CONTROL)

The following are some typical definitions of quality control and SQC:

1. Deming's definition: "Statistical quality control is the application of statistical theory and technique to all stages of production, so that products which are useful to the maximum and readily marketable can be manufactured in the most economical way"[1].

2. Juran's definition: "Quality control consists of measuring actual quality results, comparing those to standards, and taking corrective action in regard to any variances found. Statistical quality control is that part of quality control in which statistical methods are applied"[2].

3. Definition from the Japanese Industrial Standards: "[Quality control is] a system of methods to manufacture products or create services economically with the quality which meets the demands of buyers. Because modern quality control adopts statistical methods, it may specifically be called statistical quality control (SQC)"[3].

4. Definition from American National Standards Institute: "Quality control [consists of] the operational techniques and activities used to fulfill requirements for quality. Often, however, 'quality assurance' and 'quality control' are used interchangeably, referring to the actions performed to ensure the quality of a product, service or process."

Quality control in the form of comprehensive companywide quality control programs (i.e., TQC) has been introduced in every industry in Japan. Through the in-depth application of "management by objectives" and other techniques, "quality control" has developed into quality improvement programs which involve every aspect of a company's operations. Today, this expanded range of application now begins with the development of quality products that meet customer needs, includes the conventional quality improvement activities that originally took place solely in manufacturing areas, and extends to supply operations—the delivery of products to customers. Today "quality control" even encompasses the "supplying of quality" in the form of service and quality maintenance/control.

The term Total Quality Management (TQM) is now widely used in the United States. Although its fundamental meaning is the same as Total Quality Control (TQC), a term popular in Japan, it is specifically defined as follows: "Total Quality Management is the systematic approach that integrates all activities concerned with quality as they are planned and implemented throughout a company (i.e., in market research, R & D, product manufacturing, planning/scheduling, procurement, and service). Through the conduct of quality activities in these areas, products and services can be produced economically and yet at a quality level that meets customer demands. These activities are conducted in accordance with each company's plan for the achievement of important organization-wide goals which management has established in regard to quality."

SQC AND SPC

The predecessor of SQC, Mil-Spec (Military Quality Standard), was adopted by American munitions makers during World War II in order to secure high quality in mass production situations. Later Mil-Spec was widely adopted by private-sector companies as a specification for quality control. It was also introduced to Japan during the 1940s and 1950s, in the form of statistical quality control, where it was accepted in various fields, and for a time quality control was regarded as equivalent to SQC. The techniques of SQC were particularly valuable in making it possible to ascertain the causes of quality drift in manufacturing processes. For example, by elucidating the relationship between product quality and production conditions, SQC contributed greatly to quality enhancement. Moreover, SQC enabled inspection and quality improvement operations to be done more efficiently. Thus, techniques which centered on the use of SQC became the mainstream of quality control activities at that time.

In Japan, however, because SQC required significant labor for analysis and in some respects depended on experts, its utilization in manufacturing production processes was limited to only a few cases. Later, however, in order to deal with quality problems having numerous and complicated factors, easy-to-use techniques based on SQC were developed and widely adopted in applications such as the design of experiments. An excellent example of such a technique is the *Taguchi Method.* This technique was utilized broadly in R & D departments, in fundamental experiments, in the analysis of quality factors occurring in complicated manufacturing processes, and in "possible cause" investigations. It produced good results.

Furthermore, in parallel with the spread of companywide Total Quality Control to various industries and its growing use to solve important quality problems, quality factors in all areas (such as R & D and production processes) became more complicated. Not only did problems become more complex and advanced, but quicker response was required. Therefore, it became difficult to solve quality problems through conventional approaches. Problems had to be examined more deeply and dealt with at a fundamental level. In this context, SQC became the method of choice for problem solving, and it was widely adopted. In addition, there was a growing need to implement quality control on an "in-line" basis. This resulted in attempts to apply SQC in real time, as part of programs for maintaining quality and dealing with quality improvement at the factory level. This approach has continued to the present time.

Through the series of developments just discussed, SQC has become broadly adopted in many areas, particularly in application to complex quality factors. In contrast to Statistical Quality Control, which is used with a broad meaning, Statistical Process Control (SPC) is generally used in the narrower context of analysis of quality factors at the process level. SPC is also used to select corrective actions (which in Japan we refer to as *countermeasures*). In spite of this difference in usage, however, both techniques are quite similar.

QUALITY CONTROL AND QUALITY IMPROVEMENT

The history of quality control goes back to 1931, when Mr. Shuhart of Bell Laboratories in his paper, "Economic Quality Control of Industrial Products," first introduced a new way of thinking called "quality control." In this paper, he described the concept that "quality has variation, but that may be controlled to a certain desired level." The foundation of modern "control charts" is found here. Examining the history of quality control, initially the philosophy of putting primary importance on inspection was the mainstream. Later, quality-related thinking went through several phases, or "eras." There was a period when the approach was to "build quality into the production process"; then the emphasis shifted to reliability and product liability (PL); and now we are in the era of Total Quality Management (TQM).

Quality and the Control Cycle

There are various ways of thinking with regard to quality, but basic to all of them are the "character" and "function" which the subject product has. If the use of the product or the conditions under which it is used change, the required range for its performance may also vary. Therefore, quality control uses the strategy of selecting, from among the many characteristics that relate to quality in a specific case, a certain limited number of items which are then used to evaluate quality for that case. Emphasis is then placed on maintaining those items at the level of set standards.

There are two types of quality characteristics: (1) required product characteristics which can be quantified (i.e., for which true characteristic values can be determined) and (2) characteristics which cannot be directly quantified but must instead be measured by means of an alternative characteristic. For example, to measure the strength of an arc weld directly, the product must be destroyed. Therefore, substitute characteristics are measured as an alternative. These may include the width and length of the weld bead and its melt-depth.

Quality characteristics of a product can be roughly classified as either *designed quality* or *manufactured quality.* The former is also called the *target quality* (i.e., which is built into the design drawings). The design engineer has set these characteristics based on judgments from sales, production, engineering, cost, and other management considerations. The latter is also called the *built quality,* which means the quality of the product that is actually manufactured in the production process.

Different products having the same designed quality may be affected differently by various factors in the production process, so that the resulting manufactured quality becomes different. Therefore, there has recently been a growing interest in manufactured quality; the importance of quality control is being proclaimed, and active programs of quality improvement are being undertaken. "Control" in this case is to put in place a series of activities to "set proper targets and perform production in conformance to those targets, pulling in any deviant products." To put this concretely, control is composed of the four steps, (1) Plan, (2) Do, (3) Check, and (4) Action, as shown in Fig. 13.6.1. This is called the *control cycle* and is abbreviated "P-D-C-A."

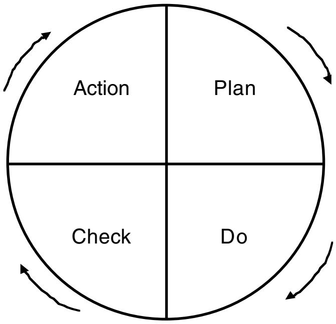

FIGURE 13.6.1 Cycle of control.

This way of thinking (i.e., repeating the control cycle to achieve a set objective) may be applied not only to quality control but also to other forms of business activity that require control. Therefore the control cycle is broadly utilized as an important technique. If the objective is quality, then whenever actual results begin to fall outside of the inspection standards, control limits, or other criteria, adequate action must be taken to maintain the objective. To be able to take such action:

1. Plans and objectives are established and standards are set. (Plan.)
2. Work is performed in accordance with the standard. (Do.) (To ensure that there is no deviation from the standard, control and education are necessary.)
3. The results are evaluated. (Check.)
4. If, upon evaluation, irregularities are found, possible causes are investigated and countermeasures are taken. (Action.)

As a result of carrying out countermeasures, more appropriate standard values may have to be defined. Then, the control cycle is repeated according to the new standards. The final step, Action, will lead to changes in the next Plan, and the P-D-C-A cycle is repeated. If this repetition of the cycle is done rapidly, quality improvement progresses quickly, but if it is done slowly, the same quality problems may continue to occur. Since the effectiveness of this approach depends on the speed at which the P-D-C-A cycle is repeated, it is important to repeat the cycle as fast as is practically possible.

The Relationship Between Quality Standards and Quality Control

In quality control there are four basic evaluation standards: (1) quality standards, (2) quality objectives, (3) quality levels, and (4) inspection standards. A brief description of each follows:

1. *Quality Standards.* These describe the quality measures that the production department must achieve through the production activity. For example, if operators on the factory floor perform work according to the operation standards, products will meet quality standards.

2. *Quality Objectives.* These are the quality parameters established during product design by the Engineering Department. They are determined in response to customer needs and input from Sales, Production, and other departments.
3. *Quality Level.* This refers to the quality standard conveyed to the customer by the Sales Department. In other words, it is the level of quality established by the company division that actually supplies the product.
4. *Inspection Standards.* These are the quality levels used by the inspection section as judgment or evaluation standards in guaranteeing the quality of the products. In other words, it is the guaranteed quality level that represents the company.

If quality is measured quantitatively, the relationship between the four standards can be expressed as follows:

$$\text{Quality objective} < \text{Quality level} < \text{Inspection standard} < \text{Quality standard}$$

Quality Assurance

Quality assurance is the objective of quality control. Achieving this objective begins with the sales department, which must accurately understand customer needs. In response to these needs, and after establishing product specifications that take into account the company strategy, product design is started. In the engineering department, the product is designed according to the established product specifications, but also considering other requirements, such as those imposed by technical realities, the production environment, customer expectations, or management priorities. In the production department, operation standards and production inspection standards are established, and production is done conforming to those standards.

Similarly, the inspection section provides feedback to the production group so that actions can be planned to build in the required quality. Inspection is conducted to maintain a product quality level that will satisfy customers and meet the policies of the company. Recently we have entered an era of social responsibility on the part of businesses, so that in the case of product defects, companies will have to accept the responsibility for compensating the customers affected. This is called *manufacturer's liability,* and it has become a major issue for management.

Related to this, many companies are launching programs of technical countermeasures aimed at increasing product quality, reliability, and integrity in situations where products are used for long periods of time. One such program, called "Fail-safe and foolproof," has recently been developed; its function is to prevent accidents when the product is used and/or to preclude misuse of the product.

The following are descriptions of several of the basic terms used in relation to quality control:

1. *Quality assurance (QA).* Quality assurance is the "systematic activity that a manufacturer performs in order to guarantee a level of quality which fully meets the demands of the customer." The following principles are necessary for implementation of a QA program:

- The quality level demanded by the customer must be correctly determined.
- The quality level demanded by the customer and required in applications must be thoroughly conveyed to the design and manufacturing departments.
- The production process must be managed so that manufactured quality conforms to demanded quality.
- Inspections must be made to verify and guarantee that manufactured products conform to the demanded quality level.

2. *Demanded quality.* The first step of quality assurance is to identify the level of demanded quality. In the case of production to stock (i.e., for future sale), the specification of demanded quality becomes difficult because the customers are numerous and not clearly identified. In such situations, market research is used to understand the diverse needs of customers. At the same time, when putting such products on the market, instructive material explaining the product and describing its correct usage should be provided to prevent misunderstandings or misuse of the product.

3. *QA activities.* To implement an effective QA program, a system needs to be established to ensure that all the actions described among the previously listed principles are performed. The implementation plan starts with the characterization of demanded quality through market surveys conducted by the sales department. Once demanded quality is understood, the next steps of product development and product design are undertaken based on the demanded quality. Thereafter, in the manufacturing and QA departments, operation standards and inspection specifications are created and production processes are established. Based on these standards, training of the operators takes place and subsequently the actual production effort begins.

In the production department, quality control and quality assurance activities include the following:

- Inspection of incoming materials and parts
- Activities on the production line aimed at “building in” quality
- In-process and finished goods inspections

The product, with its quality guaranteed, is ultimately supplied to the customer, but the quality efforts must not end there. The company as a whole must guarantee quality, which requires that the sales department, while providing excellent after-sale service and claims processing, must feed the information it gathers through those activities back to the engineering and production departments. This kind of integrated approach to quality, done in a systematic way that involves the whole company, exemplifies true quality assurance.

4. *Product liability (PL).* Product liability is a responsibility that carries the threat of having to provide compensation to customers. It may be defined as “the responsibility that manufacturers and vendors have toward a person who suffers injury from using a product or to a third party who is injured due to defective design, manufacture, or labeling of the product.”

The concept of product liability originated in the United States and has spread to the rest of the world. Product liability lawsuits increase year by year and have now become a serious factor for Japanese companies to consider when deciding whether to export products.

5. *Reliability.* Related to product liability, the reliability of products has become another big issue. *Reliability* is “a measure of the degree and/or character of the time-related stability of a total product system, including its components, parts and materials.” *Durability,* expressed in terms of average product life or failure rate, is one of the elements of reliability. Therefore, reliability may also be defined as “the probability that a device or system will continue to perform its prescribed function for a specified time period under given conditions.”

Reliability does not refer solely to long product life; the degree of *maintainability*—meaning that even if a nonfatal product breakdown occurs, it can be readily repaired and the product quickly restored—is also an important element in reliability. Maintainability is defined as “the degree and character of a product’s ease-of-maintenance, considering all the repairable systems, devices and parts which make up the product.”

As a measure of reliability, *availability,* which combines the effects of both durability and maintainability, may be used.

$$\text{Availability} = \frac{\text{operable time}}{\text{operable time} + \text{nonoperable time}}$$

To increase reliability, the most important point is to incorporate it into the product design. One method of accomplishing this is to design the product system such that if a part breaks down, it does not cause a fatal product failure. This approach is called the *fail-safe* system. Similarly, the approach of designing in features such that the product system will not suffer damage in the case of an operator mistake is called the *foolproof* method.

TYPICAL SPC TECHNIQUES

At the time that quality control began to be widely accepted, statistical quality control was the mainstream. One typical SQC technique, the *design of experiment* method, was applied in various fields and produced excellent results. However, this method involved burdensome calculations, so its use gradually became limited to a few specific areas.

Later, multivariate analysis methods and quality engineering made important advances, and concurrently progress was made in conventional quality improvement activities at the factory level. In this climate, statistical techniques came to focus on activities which went back to their original forms, in which SPC techniques had been applied.

In this section, three typical SPC techniques that are in current use are introduced: (1) design of experiments, (2) multivariate analysis, and (3) quality engineering.

Design of Experiments

What is "Design of Experiments"? Typically the problems companies face do not consist of just a single element. In most cases, several factors are involved in a complicated relationship. To begin an analysis of problems which have occurred and come up with countermeasures to prevent a recurrence, it is essential to first understand what factors (possible causes) are having an effect on the problem areas (characteristics). Several basic techniques are used to envisage the relationship between the characteristics and factors (i.e., the "cause-and-effect" relationship). These include:

- Cause-and-effect diagrams
- System diagrams
- Relational diagrams
- Other visual tools

However, the information provided by these techniques is, after all, nothing more than opinions. These opinions must be tested experimentally (through test runs, etc.) and corroborated. The "design of experiments" method is employed to do that.

In general, in scientific disciplines, when conducting experiments to verify opinions or hypotheses, it is desirable not to have dispersion (experimental error.) In fact, a good experiment is one that has "no experimental error and zero dispersion of measured values." In contrast, the basic way of thinking of design of experiments, as utilized in quality control, pays attention to the existence of dispersion. It also (according to JIS 8101) consists of designing experiments so that they can be arranged reasonably to analyze a process, economically yet accurately. Design of experiments, as used in quality control, must come up with innovative ways of defining and organizing the experiment(s) and analyzing the results, so that the effect of each causative factor can be evaluated in the most efficient manner. To do this, some of the main techniques applied are:

1. Methods for the economic planning and design of experiments (e.g., factor layout methods)
2. Methods for analyzing experimental results statistically and reaching conclusions (dispersion analysis methods)

THE ROLE OF STATISTICAL PROCESS CONTROL IN IMPROVING QUALITY

To solve problems arising from actual phenomena, the essential elements are experimental planning and assessment and analysis of experimental data. Experiments must be designed so that accurate and reliable data is obtained cost-effectively.

Practical Design of Experiments. In conducting the design of experiments, the number of experiments required will vary according to the number of causative factors. Even for two-level experiments, the number of experiments required may increase further upon considering the interaction between the main causative factors. Figure 13.6.2 provides a table for determining the number of experiments needed to achieve an adequate level of accuracy.

Number of Factors	4	5	6	7	8	9	10	11	12
Main effect	4	5	6	7	8	9	10	11	12
Interaction of 2 factors	6	10	15	21	28	36	45	55	66
Interaction of 3 factors	4	10	20	35	56	84	120	165	220
Interaction of 4 factors	1	5	15	35	70	126	210	330	495
Interaction of 5 factors		1	6	21	56	126	252	462	792
Interaction of 6 factors			1	7	28	84	210	462	924
Interaction of 7 factors				1	8	36	120	330	792
Interaction of 8 factors					1	9	45	165	495
Interaction of 9 factors						1	10	55	220
Interaction of 10 factors							1	11	66
Interaction of 11 factors								1	12
Interaction of 12 factors									1
Main effect + Interaction of 2 factors	10	15	21	28	36	45	55	66	78
Interaction of 3 or more factors	5	16	42	99	219	466	968	1981	4017
Number of experiments	16	32	64	128	256	512	1024	2048	4096

FIGURE 13.6.2 Main effect, interaction, and number of experiments in experiments of 2^n-type factors.

However, even if interaction of a higher order (three factors or greater) exists, there are many cases where action is difficult to take, or interpretation of the physical results is difficult to do. Besides, based on experience, it is assumed that in most cases the effect of high-order interaction is small. Therefore, it is not always necessary to conduct experiments for all the combinations of factors; in the case of unnecessary interactions or interactions of high order, experiments need not be conducted. What is needed instead is a practical design of experiments that reduces the scale of the experimentation. This approach, whereby experiments are only done for that portion of the possible combinations of factors which is expected to be most meaningful, is called the *partial execution method.*

A practical method has been developed, which results in high efficiency with a small number of experiments and offers simplicity in the layout of factors and method of analysis. It is called the *orthogonal chart method.* Because this approach offers many advantages, its use has spread rapidly and it has been adopted in a variety of cases:

- The method can be applied without much knowledge of theory and through mechanical operation.
- Many factors can be built into the experiments without enlarging their scale.
- Since the scale of experiments is small, it is easy to conduct the experiments.
- Analysis of experiment data is easy.

Multivariate Analysis

Definition of "Multivariate." Most of the problems that all of us deal with in our daily work have multifaceted characteristics. The usual case is that those characteristics must be considered in respect to various references, and thus can only be understood by examining various types of data. Such data is called multivariate (multicharacteristic) data. For example, considering the product quality of an engine block, it can be described in terms of multivariate data such as: dimensions, hardness, material characteristics, and processing conditions. Another example is optimizing the ratio of orders received as a fraction of sales calls made. This problem also has multivariate data, such as the salesperson's product knowledge, information about competitors, and negotiation skills, and these data must be utilized in a comprehensive manner to achieve an optimal solution.

Even if one has specialized knowledge regarding a certain problem, predicting the outcome when several characteristics are varied at the same time can often be difficult. Multivariate analysis is the method used to evaluate such multivariate data precisely. Figure 13.6.3 shows the situations for which multivariate analysis is the preferred approach.

Classification		Technical Knowledge (specialized know-how)	
		Sufficient	Insufficient
Data	Available	Make a technical judgment	Utilize multivariate analysis method
	Unavailable	Make a technical judgment	Research available materials Consult an expert

FIGURE 13.6.3 Analytical approaches depending on the availability/nonavailability of specialized knowledge and/or data.

Definition of the Multivariate Analysis Method. The multivariate analysis method is a technique for simultaneous analysis of data that have cross-correlation, while taking into consideration the coefficients of correlation.

If certain characteristics are statistically mutually independent (i.e., have no correlation), it is necessary to analyze the characteristics one by one. However, with actual characteristics there is generally some correlation, to a greater or lesser degree, so that if monovariant analysis is applied to each characteristic, elements common to various characteristics will be repeatedly evaluated. Therefore, instead of analyzing each characteristic individually (monovariant analysis), a simultaneous analysis technique is used that recognizes correlation coefficients. The generic term for this method is *multivariate analysis.* It is important that the conclusions gained through this analysis method be comprehensively evaluated, considering a variety of related technical factors, such as the theories of the specific field and the experience and knowledge of the person doing the analysis. In this way the multivariate analysis method summarizes data on many characteristics and provides usable material for making overall judgments.

Types of Multivariate Analysis Methods and Their Special Features. From the practitioner's viewpoint, multivariate analysis methods can be classified roughly in two groups:

1. Multivariate analysis methods that are used to find overall characteristic values: These are methods for summarizing the dispersion and covariance relationships, as well as the correlation of one set of multivariate data in the form of a small number of independent (noncorrelated) general characteristic values.

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2. Multivariate analysis methods used for forecasting: With these methods, the characteristics under examination are divided into two groups—object (target) variables, and description variables. These methods are used to forecast target variables, based on information gathered regarding description variables.

Quality Engineering

Definition of "Quality" in "Quality Engineering." In *quality engineering, quality* is defined as "the losses that a product causes to customers after shipping." These losses may include: (1) losses caused by variation in the functioning of the product, and (2) losses due to various troubles caused by the product (including excess application costs).

Good quality requires that there be no variation in the intended function and that losses caused by product trouble as reflected in application costs (i.e., negative side effects) be minimal.

Quality Problems. Most quality problems are problems of variation. Instability of function occurs due to variations in different factors. These variations may be likened to "noise" which, in a mathematical sense, consists of unwanted variations imposed on the desired waveform. This "noise," in turn, may be due to:

1. Environmental conditions (external noise)
2. Deterioration (interior noise)
3. Product-to-product differences

Countermeasures to Solve Quality Problems. To solve the problem of variation, which is the root of quality problems, it is necessary to "stabilize design and production technology to reduce or eliminate the potential influence of noise." Quality engineering solves quality problems by introducing a new way of thinking: "design for stability" = "parameter design." The following is a comparison of this "parameter design" approach to the conventional design method.

Conventional Approach. Based on intended product functions, parameters are chosen and characteristic values are established which exactly match target values. As a result, after the product is completed the problem of variation in function (characteristic values) may occur.

Parameter Design. First, a "parameter study" is done to build in the function required of the product. Second, for the selected design, parameter optimization is done through two stages:

- Stage one: stabilization of function (characteristic values)
- Stage two: adjustment to achieve target values

As a result, stabilized target values can be secured, so that the product function (characteristic values) will not be impacted by noise. As an approach to producing good, low cost products, conventional nonlinear methods have been used. However, in parameter design, for the evaluation or validation step, we are proposing the application of the concept of "SN ratio" (signal-to-noise ratio), which is used in the field of communication engineering.

In parameter design, the factors that affect the intended function of a product are classified as follows:

1. *Controllable factors.* These are called *design constants* or *design parameters.* The center value or level is determined by the designer or production engineer.
2. *Tolerance factors.* These are called *noise,* and they are a cause of variations in the intended function of a product.

3. *Adjustable factors.* Among the controllable factors, the "adjustable factors" impact the size of output-related characteristic values. They can be adjusted to bring characteristic values into alignment with target values.
4. *Signal factors.* Related to input and output, these are input values that can be set to change an output target value.

The following benefits can be gained by introducing parameter design:

- Quality level improves by reduction of variation in product function (characteristic values).
- Cost reduction through quality enhancement.
- Stabilization of function becomes possible in the early stages of product development, and development efficiency increases.

BUILDING IN QUALITY THROUGH SPC

In the past, when quality problems occurred in production processes, quality improvement activities, such as QC circles, were conducted in the factory and significant results were obtained. In addition, many quality problems were solved by vigorous activities on the part of production engineering departments, using such tools as design of experiments, multivariate analysis, and quality engineering. Today, however, it is difficult to specify possible causes of quality problems, since there are many causative factors resulting in problems. For this reason, it has become especially important to examine each kind of problem and apply the most suitable technique for solution.

In this section, specific methods are explained, and at the same time, actual quality problems encountered at various factories are introduced. The analytical techniques used and the methods employed for solving the problems will also be described.

Quality Improvement Activities Employing SPC, As Used In Factory Situations

The necessity for quality control originates from the fact that there is variation in (dispersion of) quality. To deal with this variation, statistical quality control (SQC) is employed. The possible causes of quality variation are called *factors,* and the technique of classifying major factors is called the *stratification method.* Each classified stratum indicates a certain quality level, and pulling out samples of quality from this stratum is called the *sampling method.* This method is intended to estimate the quality of the population from which the sample was taken, and further to enable assumptions to be made about the overall quality level. This information then becomes the basis for pass/fail judgments.

Of the various quality improvement activities conducted in manufacturing situations, *QC circle activity* is one of the most effective options. QC circles are a type of autonomous activity in which employees tackle quality problems arising at their workplace. They generally use the so-called "seven tools of quality" as one way of employing SPC, and excellent results are often obtained.

Because this method has become a basic part of quality improvement, it is applied not only among operators in a factory setting, but to other areas as well, such as white-collar work, where it has also produced excellent results. Creating a workplace atmosphere where operators make it a habit to undertake autonomous activities, to improve not only quality but productivity and work environment as well, is an important task for corporate management.

Quality Enhancement Activities Based on Workplace Improvement—Typical Methods. The so-called "seven tools" that are used for quality-enhancement activities based on workplace improvement consist of:

- Cause-and-effect diagrams
- Pareto charts
- Graphs / control charts
- Check sheets
- Scatter diagrams
- Stratification
- Histograms

In the following paragraphs, each of these tools will be introduced in detail:

1. *Cause-and-effect diagrams.* These are also known as *fishbone* diagrams. They provide a means for analyzing possible causes of expected defects in order of their importance. The factors which impact the characteristic values that determine quality are ranked in order of importance—as first, second, and third order, and smaller if necessary—and are represented by successively smaller bones. For example, in the case that a few first order factors are expected in regard to a certain defect-causing characteristic value, an equal number of bones would be drawn in, pointing to a "backbone," and named. Then, for any of the factors represented by these bones, if there are second-order factors, those would be added on to the bone pattern. In this way, a diagram is developed to analyze the factors causing defects, and when a defect occurs, the diagram can be used to isolate the probable cause.

   Of course, it is necessary to conduct a separate examination to determine whether the cause suggested by the chart is the real cause or not. An example of such a fishbone-style cause-and-effect diagram is shown in Fig. 13.6.4.

2. *Pareto charts.* Pareto charts quantify defective or flawed products and product failures, and classify them into groups according to symptomatic phenomena or possible causes. It takes the form of a bar chart, ranking the groups from largest to smallest; furthermore, a

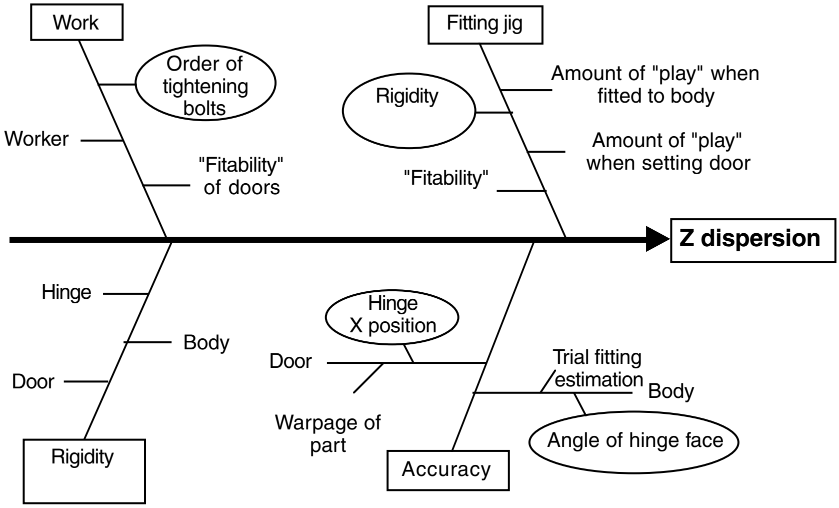
Work
Order of tightening bolts
Worker
"Fitability" of doors
Fitting jig
Rigidity
Amount of "play" when fitted to body
Amount of "play" when setting door
"Fitability"
Z dispersion
Hinge
Body
Door
Rigidity
Hinge X position
Door
Trial fitting estimation
Body
Warpage of part
Angle of hinge face
Accuracy

FIGURE 13.6.4 Fishbone-style cause-and-effect diagram for fitting doors to auto bodies.

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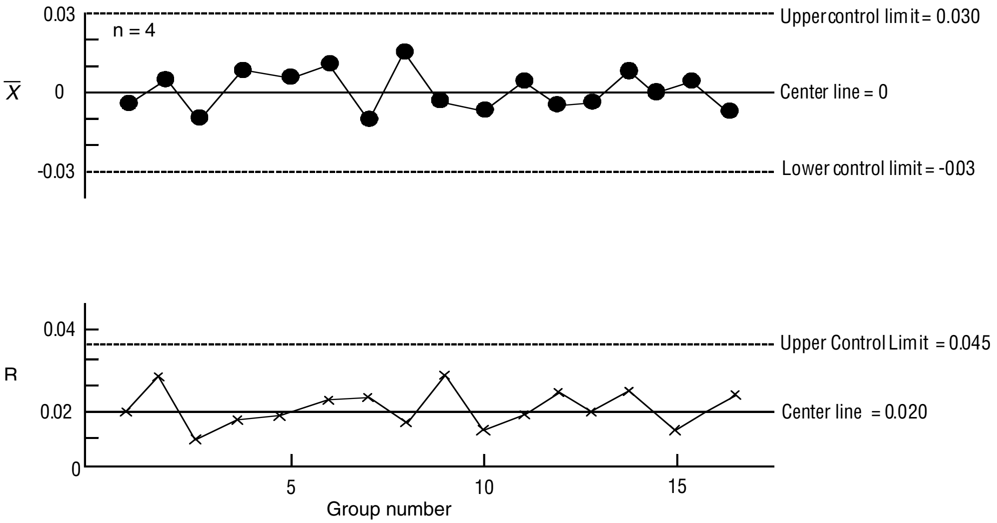
line graph is usually shown across the top showing the cumulative percentage of the included groups. By creating this Pareto chart, it becomes clear which causes are most frequent and the degree of impact of each. In this way, the areas which need countermeasures to abolish the possible causes can be identified. In general, big improvements can be gained by focusing on the groups with the highest rate of occurrence.

3. *Graphs and control charts.* To explain quality issues, graphs provide an effective technique for "visual control." Many types of graphs, including bar charts, line graphs, and pie charts, are frequently used. Control charts refer to the approach of observing over time the variations of characteristic and non-conforming values, and evaluating changes and trends. In these charts, upper and lower limits are set, and these define the evaluation standards for determining "pass or fail." The chart is used to judge whether changes are indicative of a problem and require countermeasures, or not. An example of a control chart is shown in Fig. 13.6.5.
4. *Check sheets.* Check sheets make it easy to see which failure categories account for the largest number of failures and defects. They are also used for daily control and are valuable in enabling changes in quality to be recognized at a glance. In this way, it is possible to determine where to apply countermeasures and to predict the effect. Also, if a check sheet of event frequencies is created, it can be used as a histogram.



An $\bar{x}$-R control chart is used to monitor production processes as follows: periodically a small number of consecutive products (e.g. 5) from an assembly line or other manufacturing operation are checked for a certain quality-related parameter. For each group, $\bar{x}$ (the average value of the parameter) and R (the range of values of the parameter) are measured. These two values are entered into a two-part "$\bar{x}$-R Control Chart" as shown above. The horizontal axis is directly related to time, since a new group is selected and examined after a set time interval.

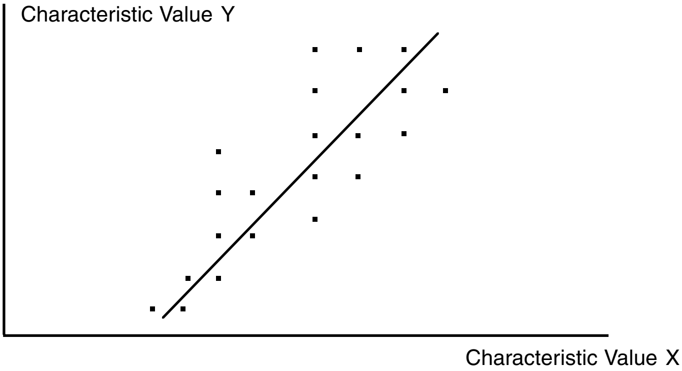
Monitoring the average value, $\bar{x}$ provides an early warning of a trend deviating from the desired center line, while monitoring R, the range, alerts the company to a problem of wider dispersion of the value, even though the average may be relatively constant.

The above example relates to the monitoring of a certain "hole position" in an auto assembly application.

FIGURE 13.6.5 Example of an $\bar{x}$-R control chart.

5. *Scatter diagrams.* Scatter diagrams can express graphically a group of data points relating two factors. From such charts, it is possible to study the relationship between two factors and to find the correlation between possible causes. In many cases, these diagrams are used to express the relationship between a cause and its effect as a numerical formula and to find an actual correlation value.

   From the scatter diagram in Fig. 13.6.6, it is clear that there is a straight-line relationship between X and Y. This approach is called *regression analysis,* and the linear relationship can be found through a "least squares" analysis.



The trend line, which is usually derived by the "least squares" method, is the best fit for a straight line correlation between the two characteristic values, based on the available data. It would be described as Y=aX + b, where "a" is the slope of the line, and "b" is the intercept of the line with the Y axis.

FIGURE 13.6.6 Scatter diagram.

6. *Stratification.* Stratification is a method which classifies collected data according to factors (causes) and is then used to show visually which factors have an influence on a given quality problem. In contrast to methods of solution, this approach is more effective in helping determine the proper viewpoint. The possible cause of failure cannot be specified if all defective products are lumped together. Only by stratifying the failures according to causes can the probable cause(s) be identified. An important consideration is the method of stratification and how to find the best approach for identifying the possible causes of the failures.
7. *Histograms.* Histograms are diagrams which clearly show how data on measured values is distributed. It is hard to draw conclusions or understand the total situation, simply by looking at the numerical values of measurements. By indicating standard values in the diagram, however, the overall distribution and its relation to the standard can be judged. In this way histograms describe the relation between stratification class and numerical values.

Process Control and Improvement Activity. Control of the production process consists of managing the total process so that it creates a level of quality that conforms to the "designed quality." In concrete terms, this consists of a flow, the first step of which is to create a QC process chart showing quality-related items which must be controlled in the major production processes. Based on the QC process charts, operation standards are set and operators are thoroughly trained. Next, for each process, a check sheet is created which contains all the con-

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trol items necessary for process control, and operators are required to make daily checks as a form of autonomous management. When variables cannot be contained within the set limits, the causes must quickly be found. Then countermeasures must be designed and implemented as necessary and other actions taken to prevent the reoccurrence of defects. To come up with countermeasures against failures, histograms, scatter diagrams, control charts, and cause-and-effect diagrams are created, so that causes can be identified and improvement measures planned. Improvement will be determined. Companies conduct their manufacturing activities while facing a variety of problems. The real key to solving most product problems, however, is achieving stable quality, and the corporate policy of putting quality at the center of "improvement activities" is very important for company survival.

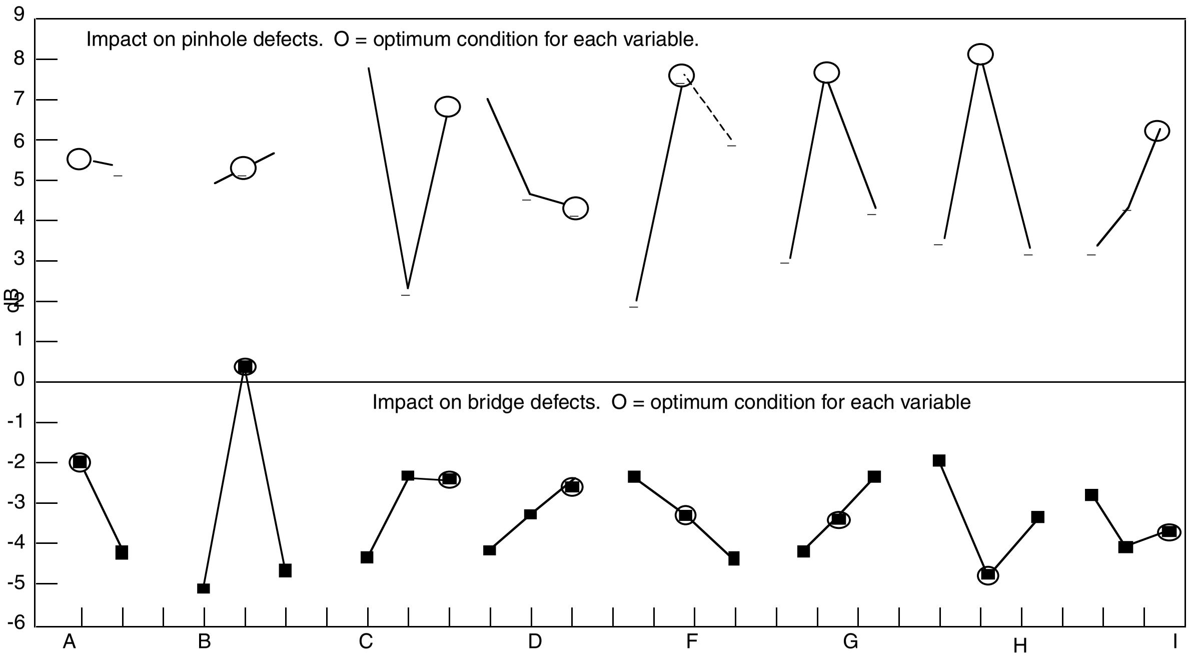
Quality Improvement Through Application of Quality Engineering (the Case of an Electronics Parts Factory)

This case is from an electronic parts factory in Company S, which had a lingering problem with bridges, pinholes, and other such soldering defects. Through the application of quality engineering, the problem of bridge-type soldering defects was solved. The procedure was as follows:

1. *Objective.* By using the design of experiments approach (the Taguchi Method), find the most suitable conditions for soldering.
2. *Setting the target and clarifying possible causes.* Set a goal of reducing solder defects by 50 percent. Through the use of "cause-and-effect diagrams," identify factors considered to have an influence on achieving this goal. The targeted defect types were solder bridges and pinholes only.
3. *Scale of the experiment, controllable factors, and error factors.* Since there were as many as eight controllable factors, the experiment used an L 18 orthogonal chart, and error factors were distributed outside it. Two or three test values were selected for each controllable factor.
4. *Experimental results.* The defects that occurred in the experiments were expressed as percentages. Converted to signal-to-noise ratios (SN ratios), the defect rate for each value of each controllable factor is shown in Fig. 13.6.7.
5. *Cause-and-effect diagram.* The cause-and-effect relationship of the data gained through the experiments is shown in Fig. 13.6.7. The diagram shows the impact on both solder bridge and pinhole defects for each of the tested values of each controllable factor. Examining this impact enabled optimum values to be chosen for each factor.
6. *Revised conditions.* New manufacturing conditions were established, adopting the optimum values determined through the cause and effect analysis. These new conditions are summarized in Fig. 13.6.8.
7. *Confirmation experiment.* A confirmation experiment was done, under the conditions shown in Fig. 13.6.8, and favorable results were obtained.
8. *Improvement situation.* Bridge defects in the soldering process were reduced to one tenth of their previous level. In this part of the project, however, it was not possible to reduce soldering defects of the pinhole type.

Quality Improvement Through Application of SPC

The four cases shown in the following sections are examples of quality improvements made at an auto body plant (Company N). The improvements were accomplished through the application of SPC methods, including design of experiments, multivariate analysis, and quality engineering.



Key to variables ("controllable factors")

A	Timing of reflow
B	Printed Circuit Board (PCB) direction
C	Nozzle width
D	Dam height
F	Solder temperature
G	Specific gravity of flux
H	Pre-heat temperature
I	Conveyor speed

For each variable, two or three practical values were tested. The value which resulted in the best combined effect, in reducing both pin holes and bridges (as measured in terms of decibels [dB] --i.e. Signal to Noise ratio) was selected as one of the new process conditions.

FIGURE 13.6.7 Example of a cause-and-effect diagram for a soldering process.

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Factor	Revised Process Conditions	
	Condition No. for optimum results.	Newly selected values for each process condition, based on the experimental results
A	1	Soldering reflow: no delay
B	2	Printed circuit board (PCB) direction : Normal
C	3	Nozzle width = 19 mm.
D	3	Solder dam height = 13 mm.
F	2	Solder temperature = 250° C (normal)
G	2	Flux specific gravity = 0.815 g / cm^3
H	2	PCB pre-heat temperature = 90° C
I	3	Conveyer speed = 1.25m / min.

FIGURE 13.6.8 Process condition chart, showing revised conditions.

Case 1

1. *Purpose.* In the press fabrication area, create a numerical formula for predicting plate thickness at the points where auto body panels are joined to pillars. Due to increased complexity of the body side panels, cracking at the points where they are joined to pillars was feared. The objective was to develop a statistical tool that would feed back quantitative results as to the quality of the forming process.
2. *Analysis.* The factors thought to affect the circumference of the part and material inflow included material inflow in the area of the door opening, and stretching of the material itself. These factors were evaluated using the company's know-how, and descriptive variables were established as follows:

   Y: Rate of reduction in plate thickness (%)
   Rs: Radius of side-view (mm)
   $r1$: Radius of cross section (mm)
   $\theta 1$: Angle of side-view of pillar part
   L: Width of shaped surface of vertical wall face (mm)
   D: Depth of pillar part of unit (not including height of stepped portion) (mm)

3. *Method of analysis.* Multiple regression analysis was selected. (Number of samples $N = 23$.)
4. *Description of countermeasure and predicted results.* As a result of performing a multiple-regression analysis, the following formula was derived for evaluating potential cracking:

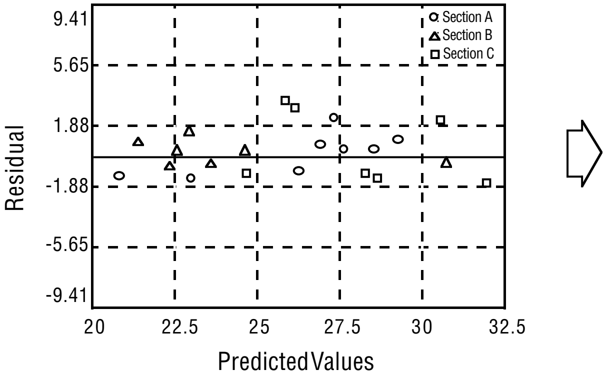
$$Y = 58{,}356 - 0.180 \times Rs - 0.209 \times r1 - 0.136 \times \theta 1 - 0.525 \times L + 0.197 \times D$$

   The result of verification (evaluation of remainders) of this formula is shown in Fig. 13.6.9.

5. *Results.* Added to the investigation content (which was otherwise based on the company's conventional know-how) was the element of "prediction," in the form of an estimation formula. This made it possible to achieve a higher level of reliability. As a result, the project succeeded in reducing the time for feedback and for studying drawings, improved the precision of press dies, and reduced the required labor.

Case 2

1. *Objective.* Achieving stabilization of the precision of fitting the car door; i.e., reducing the number of operations related to door and striker adjustment on an auto body assembly line.



The results of a “ verification” analysis, covering the three sub-assembly sections which were evaluated, are shown at left. It is clear that the results closely match the predicted values.

The selection of new process parameters is now complete.

FIGURE 13.6.9 Scatter diagram of predicted values and residuals.

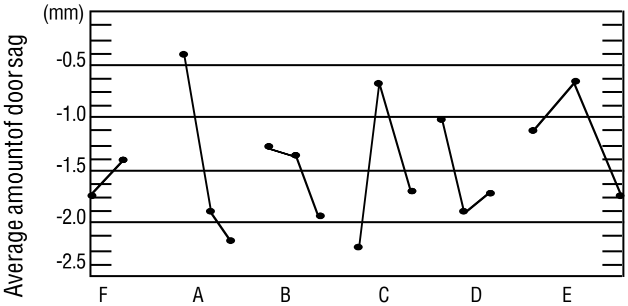
2. *Conditions for analysis and experimentation.* A cause-and-effect diagram related to variations in car door fitting was made and experiment conditions of six main cause classifications and three levels were established. Three experiments were repeated, according to an L18 orthogonal chart.
3. *Analysis technique.* Dispersion analysis was performed.

   The results of the analysis are shown in Figs. 13.6.10 and 13.6.11. They revealed the following facts.

   - The impact of the upper hinge is large; tilting of the hinge face and changes in X position together account for 60 percent of all problems.
   - The upper hinge also has a specific influence on the stability of the precision of both the lower hinge angle and the X position.
   - The effects of jig rigidity and bolt tightening sequence were negligible.
4. *Planning of countermeasures*
   - The goal was set to hold the variation of door height to within 1.0 mm in the vertical direction. Under the current method of fabrication, it was determined that the hinge face gap had to be held to within 0.5 mm.

Factor	S Sum of squares	Φ Degrees of freedom	V Mean Square	F_0 Variance ratios	Contribution rate
F) Rigidity of fitting jig	0.485	1	0.485	1.032	0.0%
A) Upper hinge angle	30.979	2	15.490	32.941**	33.1
B) Lower hinge angle	3.897	2	1.949	4.144*	3.3
C) Upper part X position	25.100	2	12.550	26.690**	26.6
D) Lower part X position	7.701	2	3.851	8.189**	7.5
E) Order of tightening bolts	2.776	2	1.388	2.952	2.0
Residual	19.749	42	0.470		
Total	90.689	53			

FIGURE 13.6.10 Verification of evaluation formula.



Experiments conducted to determine impact of various factors on door sag. Two or three test values were used for each factor.

FIGURE 13.6.11 Cause-and-effect diagram.

- Holding the hinge face gap within such a tight tolerance in turn required improvements in the configuration of the unit, in the fabrication methods, and in the door-fitting jig.

5. *Results of countermeasures.* The design of the hinge structure was changed so that the variation was reduced and, at the same time, the door-fitting jig was improved. As a result, the defect rate in terms of the evaluation value was reduced to less than 20 percent of the previous level.

Case 3

1. *Objective.* Optimize conditions for electrodeposition coating of automobile bodies; i.e., determine the optimum coating conditions so that even for a complex auto body shape the required thickness of the electro-deposited coating can be obtained uniformly, and at the same time production efficiency can be improved.

2. *Optimal electrodeposition coating.* Since the required paint film performance (film thickness) is different for different parts of the product (such as the outside surface of the car body versus the interior of the body structure), the investigation must first try to determine the conditions that will enable the required film thickness to be obtained in the minimum time for both the exterior of the auto body and the interior of the body structure.

3. *Analysis technique.* The following factors and levels were selected:

- As controllable factors, eight factors selected from among the coating factors and fabrication method factors that were assumed to influence the electrodeposition coverage
- Four levels of error factors, reflecting the coverage variation across the car body exterior and interior of the body structure
- Three levels of signal factors for electrodeposition time

Controllable factors were distributed in an L18 orthogonal chart, and experiments using test pieces were conducted to find the SN ratio and sensitivity.

4. *Determination of optimal conditions and prediction of effects.* To achieve the noted objective, optimal conditions were sought which placed priority on improving the SN ratio first and the sensitivity second. Then, while predicting the effects, a confirmation experiment was conducted.

5. *Confirmation experiment.* The results of the experiment are shown in Fig. 13.6.12. Repeatability was good for both SN ratio and sensitivity, and under optimal conditions, SN ratio was improved by 6.73dB, and the variation in film thickness across the surface (expressed as standard deviation) was reduced by about 50 percent. It was confirmed that under optimal conditions:

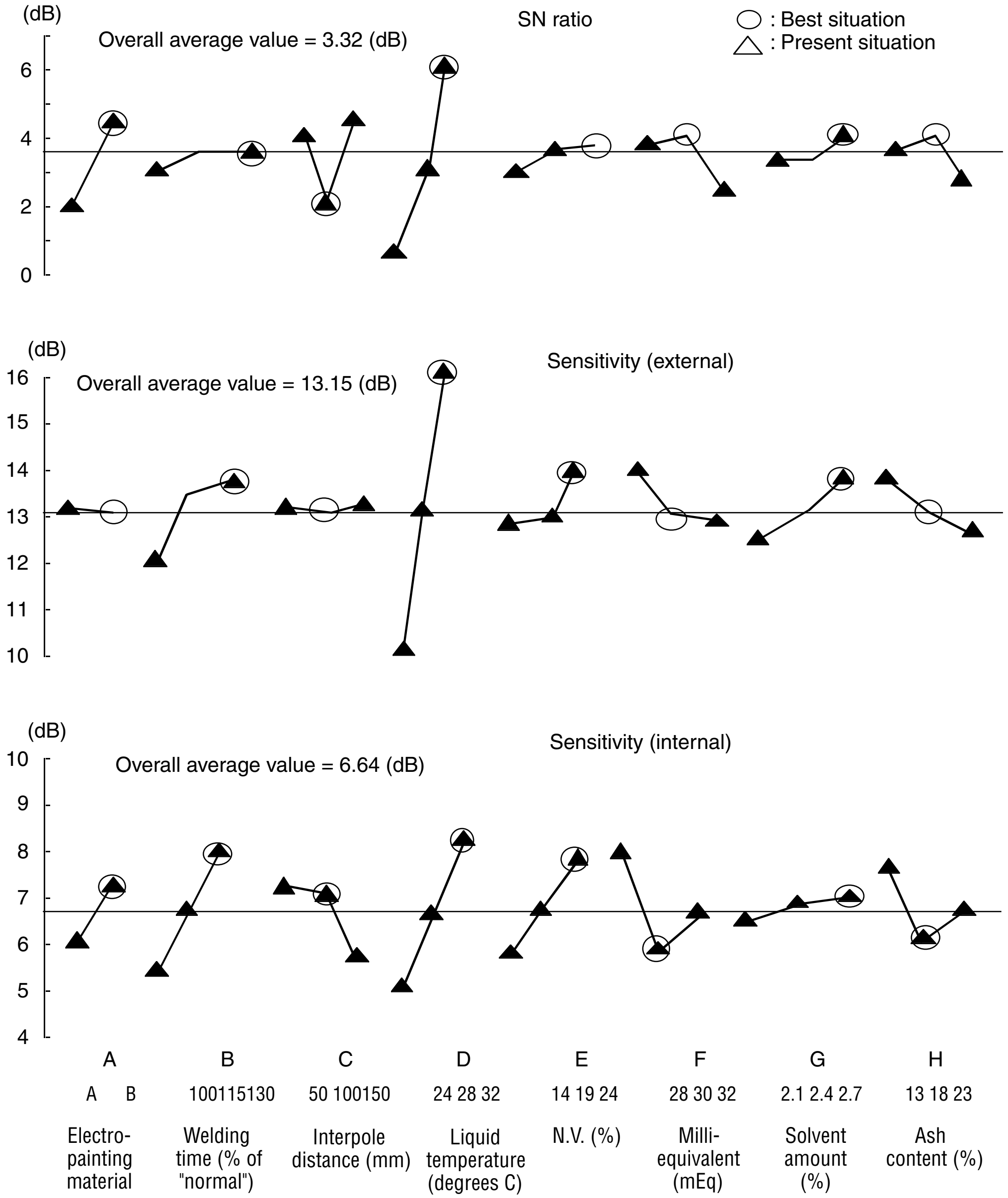


FIGURE 13.6.12 Cause-and-effect diagram, showing SN ratio and sensitivity.

- Sensitivity improved by 6 to 7dB for both the outside and inside surfaces.
- The coating thickness, which had taken five minutes to deposit under existing conditions, could be deposited in three to four minutes.
- Quality and productivity were significantly improved.

6. *Results of countermeasures.* The results that were obtained indicated that the following effects could also be expected:

- Enhancement of productivity through increased line speed, and reduction of equipment cost through shortening the length of the line.
- Reduction of the amount of coating material used by eliminating variation in film thickness.

Case 4 (An Example of SPC Applied to R & D)

1. Objective: Reduction of airflow noise of an intercooler. In the air-cooled type of intercooler (I/C) added to turbochargers (T/Cs), cooling performance drops and airflow noise occurs when the air flow passing through the tubes inside the I/C becomes concentrated in one area. The noise may reach a level that causes problems with users. The objective was not simply to apply noise suppression countermeasures, but to solve the problem causing the noise, so that the function of the I/C would be improved as well. A basic technical innovation was sought that would reduce the airflow noise phenomenon and that could also be applicable to future products.

2. *The function and parameters of air-cooled I/Cs.* The performance of air-cooled I/Cs requires that "there be little restriction of the airflow through each I/C tube and the airflow velocity be uniform at all points." It was decided to measure the volumetric flow of air and the airflow velocity, in relation to the rotational velocity of the T/C, and establish the ideal conditions for the functioning of the I/C system. This would ensure that the airflow velocity is uniform in every part of the system.

3. *Analysis technique.* Four factors were set: two signal factors and two error factors. As controllable factors, eight factors were selected, based on the manufacturer's technical knowledge of which factors had the biggest influence on airflow inside the I/C. These eight factors included dimensions, shapes, and so forth. They were allocated to an L18 orthogonal chart; experiments were conducted; and various kinds of data were gathered. This data was analyzed, and SN ratios and sensitivities were determined.

4. *Determination of optimal conditions and prediction of effects.* Optimal conditions were selected through a cause-and-effect diagram of SN ratio and sensitivity, and these were compared to existing condition values. Through this approach, it was found that under the optimal conditions, SN ratio could be improved by 7.62dB and dispersion of flow velocity reduced by 60 percent in terms of standard deviation.

5. *Confirmation experiment.* According to the experimental results, repeatability was good, and compared to the present conditions, SN ratio improved by 7.89dB, while dispersion of flow velocity was reduced by 60 percent. The results in terms of solving the airflow noise problem were also good, with the noise level under driving conditions, when airflow noise becomes the greatest, showing a reduction of about 6dB (i.e., to a level at which there is no user problem at all). Cooling performance improved by about 20 percent, compared to the existing conditions, which means the achievement of about a 2 percent improvement in the total efficiency of the engine.

6. *Summary of results.* Under optimal conditions, airflow noise was eliminated and cooling performance improved. Moreover, product cost was lowered at the same time. This experiment is an example of improvements made by an R & D division. However, such improvements also have positive impact in the manufacturing area, and therefore this example was included here.

CREATING AN AUTOMATIC QUALITY REGULATING SYSTEM BY APPLYING SPC

The technique of regulating quality in production processes in real time has been used since the 1950s, when it was developed and adopted mainly in the area of machining. Its use evolved as follows:

- *1950s.* First, in the area of grinding machines, automatic measurement techniques were applied to monitor the dressing operation and the quantity of material removed from the grinding tool. These techniques made it possible to achieve the desired level of high-precision machining, and real-time quality regulating techniques became established.
- 1970s. The scope of use of automatic measurement techniques broadened as they were applied to the achievement of improved quality assurance and productivity in automatic assembly production processes.
- 1980s. As the market demand for higher precision grew, technology was developed to enable "in-line, real-time SPC." This involved the statistical compiling of data gathered from automatic measuring equipment and the immediate feedback of decision outputs to the quality control system on the production line.

In automobile body manufacturing as well, requirements for achieving higher quality, shorter development times, and cost reduction have grown. Company N responded to these demands by developing IBS, the Intelligent Body Assembly System. An SPC system that performs in-line, real-time automatic quality regulation was built into IBS and enabled it to achieve the desired results.

The following describes the background to Company N's development of IBS and its experience with the new system.

The Necessity for Developing a New Production System in Auto Body Manufacturing

The business environment of the automotive industry is changing drastically. To respond to these changes, companies must have flexibility, and an important subject is how to increase the level of freedom for management. Flexibility in the production system itself is needed, and this means achievement of the so-called "Five As":

- Any volume
- Anywhere
- Anytime
- Anything
- Anybody

To achieve this in actual practice, the following four kinds of flexibility are required.

1. Flexibility of production centers and production volume: Any volume, anywhere
2. Flexibility of production time (timing): Anytime
3. Flexibility in product application: Anything
4. Flexibility in regard to people: Anybody

Basic Concept of New Production System

The concept of the new production system is shown in Fig. 13.6.13.

1. *Information system.* It is organized according to a matrix, vertically divided according to each level of control or administration and horizontally according to production process,

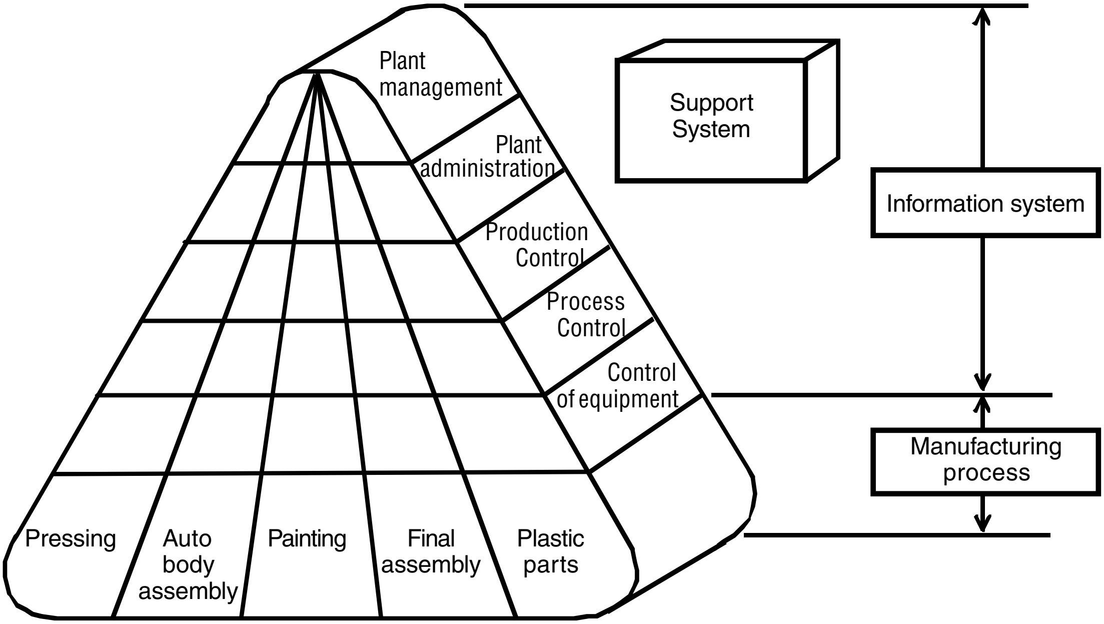

Plant management
Plant administration
Production Control
Process Control
Control of equipment
Support System
Information system
Manufacturing process
Pressing
Auto body assembly
Painting
Final assembly
Plastic parts

FIGURE 13.6.13 Concept for a new production system.

such as press, auto body assembly, etc. In each level, intelligence is built into the information system.

2. *Production process.* Important features of this process are that it interfaces with the information system without any kind of modification or remodeling of equipment hardware and is capable of immediate response.

3. *Support system.* This is an off-line system that supports the production system. It consists of the following three functions:

- During the product development stage, the ability to do computer simulations of new car prototypes
- The ability to teach the computerized production system autonomous value changes off-line
- The ability to observe the production system off-line

The corporate policy behind this new production system is achievement of "a culture where satisfaction of the customer is the primary principle." Through an "intelligent production system," the various areas of R & D and sales, as well as affiliated companies, are connected via a network. The activity of every group proceeds in synchronization based on unified information. This approach is based on the following two points:

- Simultaneous engineering: product development and manufacturing preparation proceed together
- Integration of manufacturing and sales: produce to order, in real time

Making the Auto Body Assembly Process More Flexible

The auto body assembly process at Company N consists of building up the body frame by assembling 300 to 350 press parts, using a total of 3500 to 4000 spot welds. A large number of robots are used in the welding centers. IBS was developed in order to convert this auto body assembly process to actual FMS. The objectives were as follows:

1. At any factory, to be able to instantly change to production of any of the auto body types that the company produces, simply by modifying the data related to the shape of the car body.
2. To have autonomous capability for self-checking and self-correction of product quality or self-diagnosis of equipment breakdowns, and thus gain superior quality and high utilization ratios.
3. To enable simultaneous product development and manufacturing preparation through the use of production simulation using CAD data for the subject automobile, and at the same time to reduce the time required for preparation and setup.

The basic structure of the IBS system, as actually implemented, is composed of the following:

1. *An NC locator.* This is a programmable auto body assembly jig. It can assemble the body of any car model simply by changing data.
2. *In-line auto body accuracy measuring equipment and feedback system.* One hundred percent accuracy control is accomplished through high-speed measurement of the precision of key positions on the fully assembled auto body. This is done through the use of laser sensors and other advanced measuring equipment. When a change in the precision of the car body is detected, the amount of change is instantly identified in terms of specific values, and analysis is then done automatically. The result is that the system can promptly and accurately respond to the change.
3. *Support system.* This has the features of CAD teaching and CAD simulation.

The Benefits of IBS

Through implementation of this system, the following benefits were obtained in the design area:

- Automobiles of stable and superior quality can be offered to customers in a timely fashion.
- The product features desired by customers can be developed and offered quickly.
- By conducting production simulation using CAD data, shortening of the period for new car development was achieved.

In the production area, the specific benefits were the following:

- Multitype, mixed production became possible, covering all products from the largest to the smallest automobiles made by Company N.
- Setup for model changes became possible through data changing only, and a drastic reduction in manufacturing preparation time and costs was achieved.

Through creative application of SPC, the IBS system has provided a distinct competitive advantage to Company N.

CONCLUSIONS AND FUTURE TRENDS

SPC techniques have been utilized in different contexts over the years. The case studies presented here show how companies today are effectively using SPC to solve real problems and make measurable improvements to product quality. SPC methods can be applied to problems in both R & D and production. Overhead departments can also benefit from the application of SPC methods to problems of quality.

The IBS system just described gives us a glimpse of the future. Quality considerations are applied from the earliest steps of product definition, and design and the concept of causative factors, appropriate control limits, and means of monitoring them are built into the production plan. Quality monitoring tools are integrated into an automated production system. Using SPC methods, quality data is fed back automatically to the production system and controllable parameters can be varied automatically to bring quality measures back into control. With the increase in the computing power available to manufacturing operations, expanded use of SPC techniques as part of automated production systems may be expected.

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BIOGRAPHY

Takao Tsuyuki graduated from the School of Engineering at Chiba University (Japan) in 1957. He is presently a senior consultant with JMA Consulting (Tokyo). His fields of particular technical expertise are production engineering and press fabrication technology. He is the author of several works (in Japanese), including *Techniques for Building Automated Production Lines, Engineering of Production Equipment, Strengthening the Capability of Production Engineers,* and *The Work of the Factory Manager.* He received an award from the Ministry of Labor for his work in the field of press operation safety. For many years Mr. Tsuyuki was a lecturer at the Chiba University School of Engineering.

SECTION 14

MANUFACTURING TECHNOLOGIES

Source: MAYNARD'S INDUSTRIAL ENGINEERING HANDBOOK

CHAPTER 14.1

MANUFACTURING PROCESSES

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This chapter discusses the manufacturing processes used in industry to produce discrete products (cars, aircraft, computers, appliances, machinery, plastic moldings, and glass products) from the three basic engineering materials (metals, ceramics, and polymers) and composites of these basic materials. Manufacturing processes divide into two categories: (1) *processing operations,* which transform materials into component parts, and (2) *assembly operations,* which join those component parts into products. Processing operations include shaping operations, property-enhancing operations, and surface-processing operations. Assembly includes welding, brazing, soldering, adhesive bonding, and mechanical assembly. The individual manufacturing processes in each of these categories will be defined in this chapter.

MANUFACTURING DEFINED

Manufacturing can be defined two ways: (1) from a *technological viewpoint,* and (2) from an *economic viewpoint.* Technologically, manufacturing consists of the application of physical and chemical processes to alter the geometry, properties, and/or appearance of a given starting material to make parts or products. Manufacturing also includes assembly processes in which products are made by joining multiple parts into a single entity. Processes to accomplish manufacturing involve a combination of machinery, tools, power, and manual labor, as depicted in Fig. 14.1.1(*a*). Manufacturing is almost always carried out as a sequence of operations, with each operation bringing the material closer to the desired final state.

Economically, manufacturing involves the transformation of materials into items of greater value by means of one or more processing and/or assembly operations, as depicted in Fig. 14.1.1(*b*). The essential point is that manufacturing *adds value* to the material by changing its shape or properties, or by combining it with other materials. The product has been made more valuable than the starting material through the manufacturing operations performed on it.

Our coverage in this chapter is concerned with the technological definition. Specifically, this chapter describes the manufacturing processes used in industry to make discrete items; that is, individual parts and assembled products rather than products made by continuous processes. The processes considered here are used to make products of the kind listed in Table 14.1.1, as well as the parts and materials that go into these products.

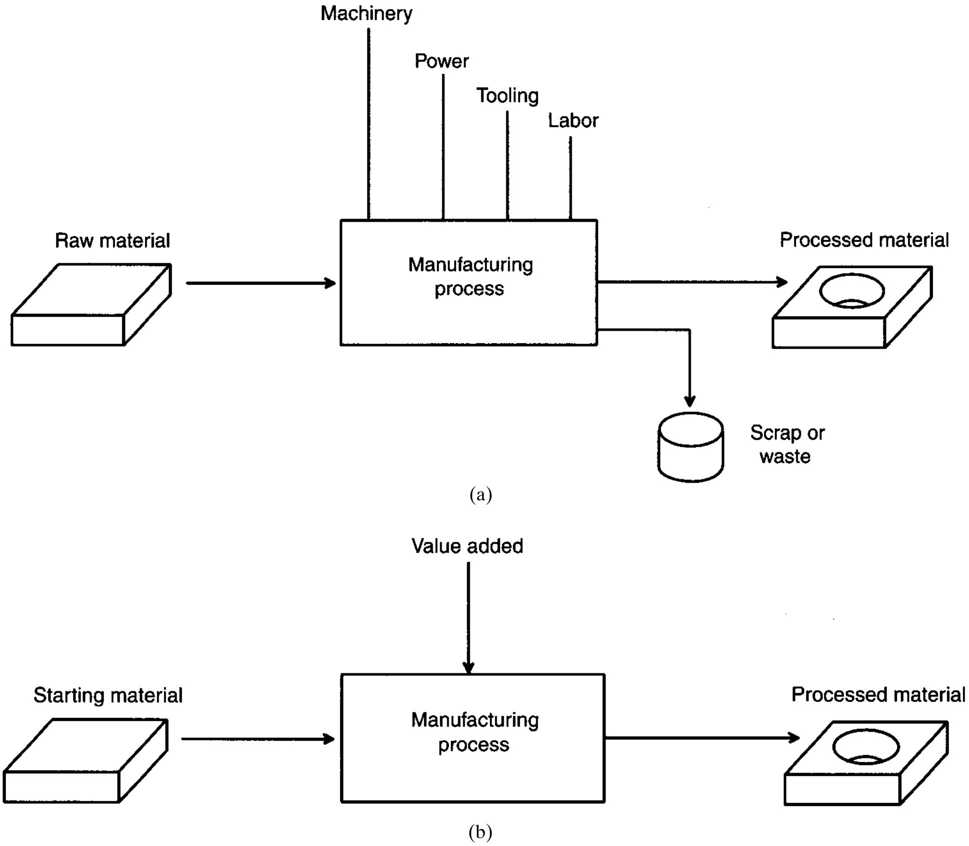
Machinery
Power
Tooling
Labor
Raw material
Manufacturing process
Processed material
Scrap or waste
(a)
Value added
Starting material
Manufacturing process
Processed material
(b)

FIGURE 14.1.1 Two ways to define manufacturing: (*a*) as a technological process and (*b*) as an economic process.

MATERIALS AND MANUFACTURING PROCESSES

Before discussing the processes used in manufacturing, it is appropriate to identify and briefly discuss the categories of engineering materials used in manufactured products. These are the materials out of which the products in Table 14.1.1 are fabricated. The reason for discussing these engineering materials is that a strong correlation exists between the type of material and the most appropriate manufacturing process for that material.

Engineering materials can usually be classified into one of three basic categories: (1) *metals,* (2) *ceramics,* and (3) *polymers.* Their chemistries and properties are different, and these differences influence the selection of the manufacturing processes that can be used to make products from them. In addition to the three basic categories, there is a fourth category: *composites*—nonhomogeneous mixtures of the other three types rather than a unique category. Definitions and examples of the four groups are listed in Table 14.1.2.

Manufacturing processes divide into two basic types: (1) processing operations and (2) assembly operations. A *processing operation* transforms a work material from one state of completion to a more advanced state that is closer to the final desired product. It adds value by changing the geometry, properties, or appearance of the starting material. In general, processing operations are performed on discrete workparts, but some processing operations are

TABLE 14.1.1 Manufacturing Industries (and Associated Products) Whose Manufacturing Processes Are Likely to Be Included in This Chapter

Industry	Typical products
Aerospace	Commercial and military aircraft
Automotive	Cars, trucks, buses, motorcycles, military vehicles
Basic metals	Iron and steel, aluminum, copper, etc.
Computers	Mainframe and personal computers
Consumer appliances	Large and small household appliances
Electronics, consumer	TVs, VCRs, audio equipment
Electronics, industrial	Sensors, process controllers, measuring instruments
Electronics, military	Weapons guidance and targeting systems
Equipment	Industrial machinery, railroad equipment, motors, pumps
Fabricated metals	Machined parts, metal stampings, tools
Glass, ceramics	Glass products, ceramic tools, pottery
Heavy machinery	Machine tools, construction equipment
Plastics (shaping)	Plastic moldings, extrusions
Tire and rubber	Tires, shoe soles, tennis balls

Source: Groover, 1996.

TABLE 14.1.2 The Four Groups of Engineering Materials

Type	Description	Examples
Metals	Metals used in manufacturing are usually *alloys,* which are composed of two or more elements, at least one of which is a metallic element. Metals divide into two basic groups:	
	1. *Ferrous.* Based on iron; they comprise more than three-quarters of the metal tonnage throughout the world.	Steel, stainless steel, and cast iron
	2. *Nonferrous.* Based on metallic elements other than iron. Among the more readily processed metals is aluminum; among the more difficult metals to process are nickel and titanium.	Aluminum, copper, magnesium, nickel, tin, titanium, and zinc
Ceramics	Defined as a compound containing metallic (or semimetallic) and nonmetallic elements. Typical nonmetallic elements are oxygen, nitrogen, and carbon. For processing, ceramics can be divided into two categories:	
	1. *Crystalline ceramics.* Formed from powders and then sintered to bond the powders.	Clay products and alumina (Al_2O_3)
	2. *Glasses.* Can be softened by heating and then formed by processes such as glass blowing and molding.	Silica (SiO_2)
Polymers	A compound formed of repeating structural units called *mers,* whose atoms share electrons to form very large molecules. Nearly all polymers consist of carbon plus one or more other elements, such as hydrogen, nitrogen, oxygen, and chlorine. Three basic categories of polymers:	
	1. *Thermoplastic polymers.* Can be subjected to multiple heating and cooling cycles without substantially altering their molecular structure; they constitute about 70% of the tonnage of all synthetic polymers.	Polyethylene, polystyrene, polyvinylchloride, and nylon
	2. *Thermosets.* Chemically transform (called *curing*) into a rigid structure upon cooling from a heated plastic.	Phenolics, amino resins, polyesters, and epoxies
	3. *Elastomers.* Also known as *rubbers,* they exhibit significant elastic behavior; hence, the name *elastomer.* They constitute about 15% of the total annual tonnage of polymer production.	Natural rubber, styrene-butadiene, neoprene, silicone, and polyurethane
Composites	A material consisting of two phases that are processed separately and then bonded together to achieve properties that are superior in certain ways to those of its constituents. Each phase is a member of one of the three basic engineering material groups.	Glass-fiber-reinforced plastic and cemented carbide (WC-Co)

also applicable to assembled items (for example, it is more convenient to paint a welded assembly after welding rather than paint the individual parts beforehand). An *assembly operation* joins two or more components in order to create a new entity, which is called an *assembly, subassembly,* or some other term that refers to the joining process (for example, *weldment* is used to describe a welded assembly). The general classification of manufacturing processes that will be followed in this chapter is presented in Fig. 14.1.2.

PROCESSING OPERATIONS

A processing operation uses energy to alter a workpart's shape, physical properties, or appearance in order to add value to the material. The forms of energy include mechanical, thermal, electrical, and chemical. The energy is applied in a controlled way by means of machinery and tooling. Human energy may also be required, but human workers are generally employed to control the machines, to oversee the operations, and to load and unload parts before and after each cycle of operation. A general model of a processing operation is illustrated in Fig. 14.1.1(*a*). Material is fed into the process, energy is applied by the machinery and tooling to transform the material, and the completed workpart exits the process. As shown in the model, most production operations produce waste or scrap, either as a natural aspect of the process (e.g., removing material as in machining) or in the form of occasional defective pieces. It is an important objective in manufacturing to reduce the incidence of waste in either of these forms.

More than one processing operation is usually required to transform the starting material into its final form. The operations are performed in the particular sequence required to achieve the geometry and condition defined by the design specification.

Three categories of processing operations are distinguished: (1) shaping operations, (2) property-enhancing operations, and (3) surface-processing operations. *Shaping operations* alter the geometry of the starting work material by various methods. Common shaping processes include casting, forging, and machining. *Property-enhancing operations* add value to the material by improving its physical properties without changing its shape. Heat treatment is the most common example. *Surface-processing operations* are performed to clean, treat, coat, or deposit material onto the exterior surface of the work. Common examples of coating are electroplating and painting, performed to protect the surface or enhance its appearance.

Shaping Processes

Most shape-processing operations apply heat or mechanical force or a combination of these to effect a change in geometry of the work material. There are various ways to classify the shaping processes. The classification used here is based on the state of the starting material, by which we have four categories:

1. *Solidification processes.* These include casting, molding, and other processes in which the starting material is a heated *liquid* or *semifluid.*
2. *Particulate processing.* The starting material is a *powder,* and the powders are formed into the desired geometry and then heated to bind the powders.
3. *Deformation processes.* The starting material is a *ductile solid* (commonly metal), which is deformed by mechanical stresses to shape the part.
4. *Material removal processes.* The starting material is a *solid* (ductile or brittle), from which material is removed so that the remaining part has the desired geometry.

Solidification Processes. In the first category, the starting material is heated sufficiently to transform it into a liquid or highly plastic (semifluid) state. Nearly all materials can be

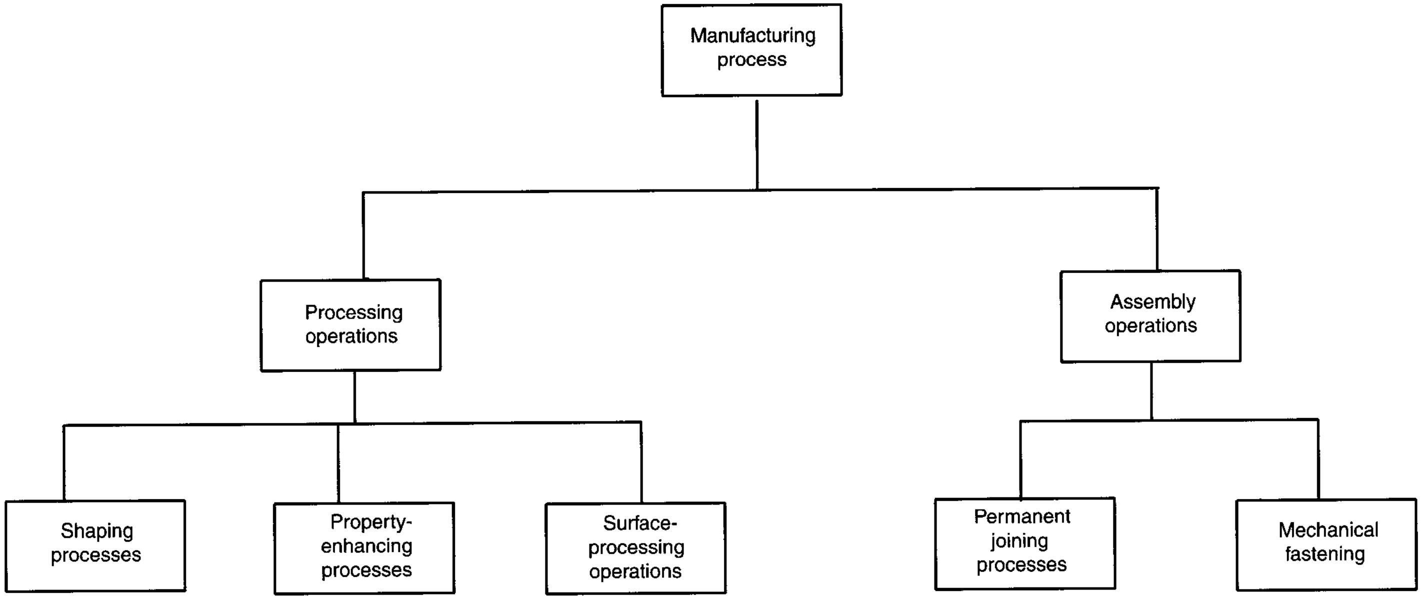
Manufacturing process
Processing operations
Assembly operations
Shaping processes
Property-enhancing processes
Surface-processing operations
Permanent joining processes
Mechanical fastening

FIGURE 14.1.2 Classification of manufacturing processes.

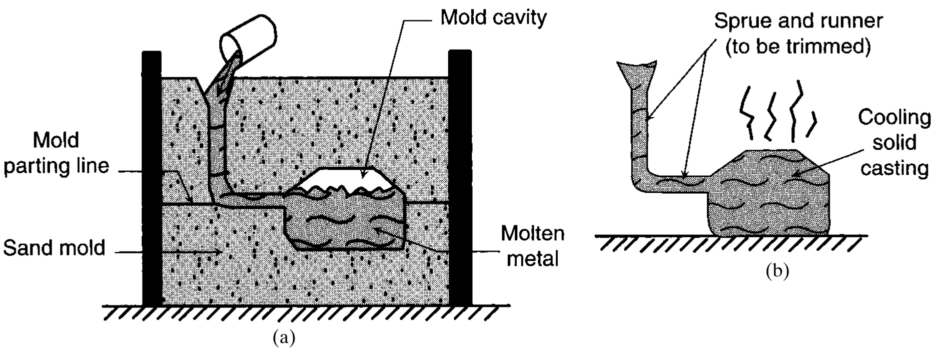

FIGURE 14.1.3 Solidification processes start with a work material heated to a fluid or semifluid state. The process consists of: (*a*) pouring or otherwise forcing the fluid into a mold cavity, where (*b*) the fluid cools and solidifies, after which the solid part is removed from the mold.

processed in this way. Metals, ceramic glasses, and plastics can all be heated to sufficiently high temperatures to convert them into liquids. With the material in a liquid or semifluid form, it can be poured or otherwise forced to flow into a mold cavity, where it cools and solidifies to take a solid shape that is the same as the cavity. Processes that operate this way are called *casting* or *molding. Casting* is the name used for metals, and *molding* is the common term used for polymers. Glassworking involves shaping of the glass while it is in a hot semifluid condition, using a variety of techniques, which include casting and molding. Polymer matrix composites are also shaped while in a fluid condition; some of the processes are the same as those used for plastics, and others are considerably more complicated. This category of the shaping process is depicted in Fig. 14.1.3.

TABLE 14.1.3 Common Casting Processes for Metals

Process	Description
Centrifugal casting	A family of permanent mold-casting methods in which centrifugal force is used to distribute the molten metal to the outer regions of the mold cavity.
Die casting	A permanent mold-casting process in which molten metal is injected into a steel (typically) mold cavity under high pressure. Common metals used in die casting include zinc, tin, and lead.
Expanded polystyrene process	An expendable mold process in which a polystyrene foam pattern (full-scale replica) of the part is used to make a sand mold. The pattern vaporizes when molten metal is poured into the mold. Also known by the names *lost-foam process, lost-pattern process,* and *evaporative-foam process.*
Investment casting	An expendable mold process in which a wax pattern (full-scale replica) of the part is coated with a refractory material to make the mold. The wax is then melted away, and molten metal is poured into the mold to make the casting. Also known as the *lost-wax process.*
Permanent mold casting	This process uses a permanent mold made of metal (e.g., steel or cast iron) constructed of two sections designed for easy, precise opening and closing. Common molding metals include aluminum, magnesium, and copper-based alloys.
Sand casting	An expendable mold process consisting of pouring molten metal into a sand mold, allowing the metal to cool and solidify, and then breaking up the mold to remove the casting. Sand molds are made by forming the sand around a *pattern* of the part to be cast. Sand casting is by far the most widely used casting operation. Common metals used in sand casting include cast iron, steel, and aluminum.
Shell molding	An expendable mold process in which the mold is a thin shell (≈10 mm thick) made of sand and held together by a thermosetting resin binder.

Some of the common casting processes are defined in Table 14.1.3. Two basic categories of casting process can be distinguished: (1) expendable mold casting and (2) permanent mold casting. In *expendable mold-casting* processes, the mold must be sacrificed (destroyed) so that the part can be removed. Accordingly, a new mold must be fabricated for every casting. In *permanent mold-casting* processes, the mold is made of metal or other durable material (ceramic is sometimes used) so that it can be used to cast many parts. These molds are designed in two parts so they can be closed (for the casting cycle) and opened to remove the cast part.

Polymers are almost always shaped by solidification-type processes. Some of the common molding operations for polymers are listed in Table 14.1.4. In addition to molding, *extrusion* is a widely used process for polymers. In polymer *extrusion,* the polymer melt is forced by compression to flow through a die orifice to form a long continuous product whose cross-sectional shape is determined by the contour of the orifice. Polymer products made by extrusion include tubing, pipes, hose, structural shapes, sheet, film, continuous filaments for textiles, and coated electrical wire and cable.

Particulate Processing. In *particulate processing,* the starting materials are powders of metals or ceramics. Although metals and ceramics are quite different, the processes to shape them in particulate processing are quite similar. The common technique involves pressing and sintering, illustrated in Fig. 14.1.4, in which the powders are first squeezed into a die cavity under high pressure. This causes the powders to take the shape of the cavity. However, the com-

TABLE 14.1.4 Common Molding Processes for Polymers

Process	Description
Blow molding	Air pressure is used to inflate a heated *parison* (starting tube-shaped blank), forcing it into a hollow geometry confined on its exterior by a mold cavity. Commonly applied to thermoplastic polymers to make plastic bottles and similar hollow containers. Two processes are used to produce the starting parison: **1.** Extrusion **2.** Injection molding
Compression molding	Molding compound (the *charge*) is loaded into the bottom half of a heated mold. The two mold halves are brought together to compress the charge, forcing it to take the shape of the mold cavity. The heated material cures into the molded part. Commonly applied to thermosetting polymers and elastomers.
Injection molding	Polymer is heated to highly plastic (almost liquid) state and forced to flow under high pressure into a two-part mold cavity where it solidifies. The mold is subsequently opened and the part removed. Applied mostly to thermoplastic polymers, less commonly to thermosets and elastomers.
Reaction injection molding (RIM)	Two highly reactive liquid ingredients are mixed and immediately injected into a mold cavity where chemical reactions leading to solidification occur. Molded parts are then removed from cavity. Common polymers used with RIM: urethanes, epoxies, and urea formaldehyde.
Rotational molding	An alternative to blow molding for larger hollow parts made in smaller quantities. Polymer powders are placed in a mold cavity. The mold is heated and simultaneously rotated around two mutually perpendicular axes, forcing the powder to contact all surfaces of the cavity to form a fused layer. The mold is then cooled to solidify the part.
Thermoforming	A flat thermoplastic sheet is heated and then formed by forcing the sheet to take the shape of a mold. Forming is accomplished in three ways: **1.** *Vacuum thermoforming.* A vacuum is used to draw the sheet into a concave mold cavity. **2.** *Pressure thermoforming.* Positive air pressure forces the sheet into a concave mold cavity. **3.** *Mechanical thermoforming.* Two matching mold halves force the sheet into the geometry of the mold.
Transfer molding	Similar to compression molding. A charge is loaded into a chamber immediately ahead of the mold cavity and heated to soften it. The softened material is then forced to flow into a heated mold, where curing occurs. Commonly applied to thermosetting polymers.

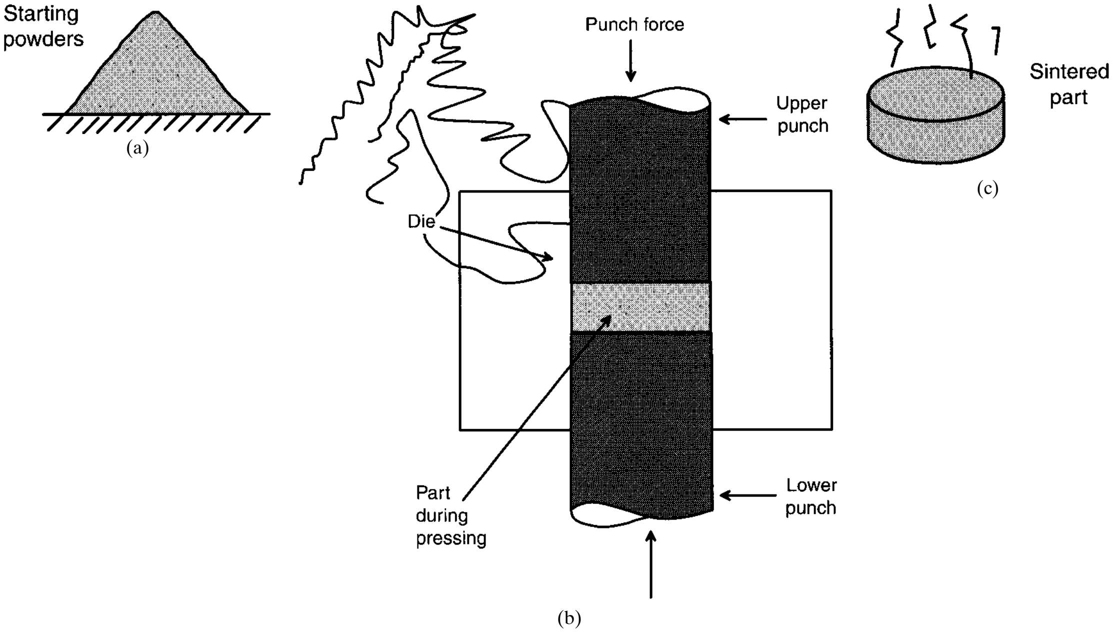

FIGURE 14.1.4 Particulate processing. (*a*) Starting material is powder; the usual process consists of (*b*) pressing and (*c*) sintering.

pacted workpart lacks sufficient strength for any useful application. To increase strength, the part is then heated to a temperature below the melting point, which causes the individual particles to bond together. The heating operation is called *sintering.*

Deformation Processes. In *deformation processes,* the starting workpart is shaped by application of forces that exceed the yield strength of the material. For the material to be formed in this way, it must be sufficiently ductile to avoid fracture during deformation. To increase ductility (and for other reasons), the work material is often heated, prior to forming, to a temperature below the melting point. Deformation processes are associated most closely with metalworking and include operations such as *forging, extrusion, rolling,* and *bar* or *wire drawing,* as shown in Fig. 14.1.5. Also included in this category are sheet-metal processes such as *bending* [as shown in Fig. 14.1.5(*e*)]. Some of the common sheet-metal operations are defined in Table 14.1.5.

Material Removal Processes. *Material removal processes* are operations that remove excess material from the starting workpiece so that the resulting shape is the desired geometry. The most important processes in this category are *machining* operations such as *turning, drilling,* and *milling,* as shown in Fig. 14.1.6. These and other machining processes are defined in Table 14.1.6. Machining is most commonly applied to solid metals. It is accomplished using cutting tools that are harder and stronger than the work metal. *Grinding* is another common process in this category, in which abrasive ceramic grits contained in a grinding wheel act as cutting tools to remove material.

A second category of material removal processes is known as *nontraditional processes* because they do not use traditional cutting and grinding tools. Instead, they make use of other energy forms such as electrical, heat, light, and chemical energy. Table 14.1.7 defines some of the common nontraditional processes.

MANUFACTURING PROCESSES

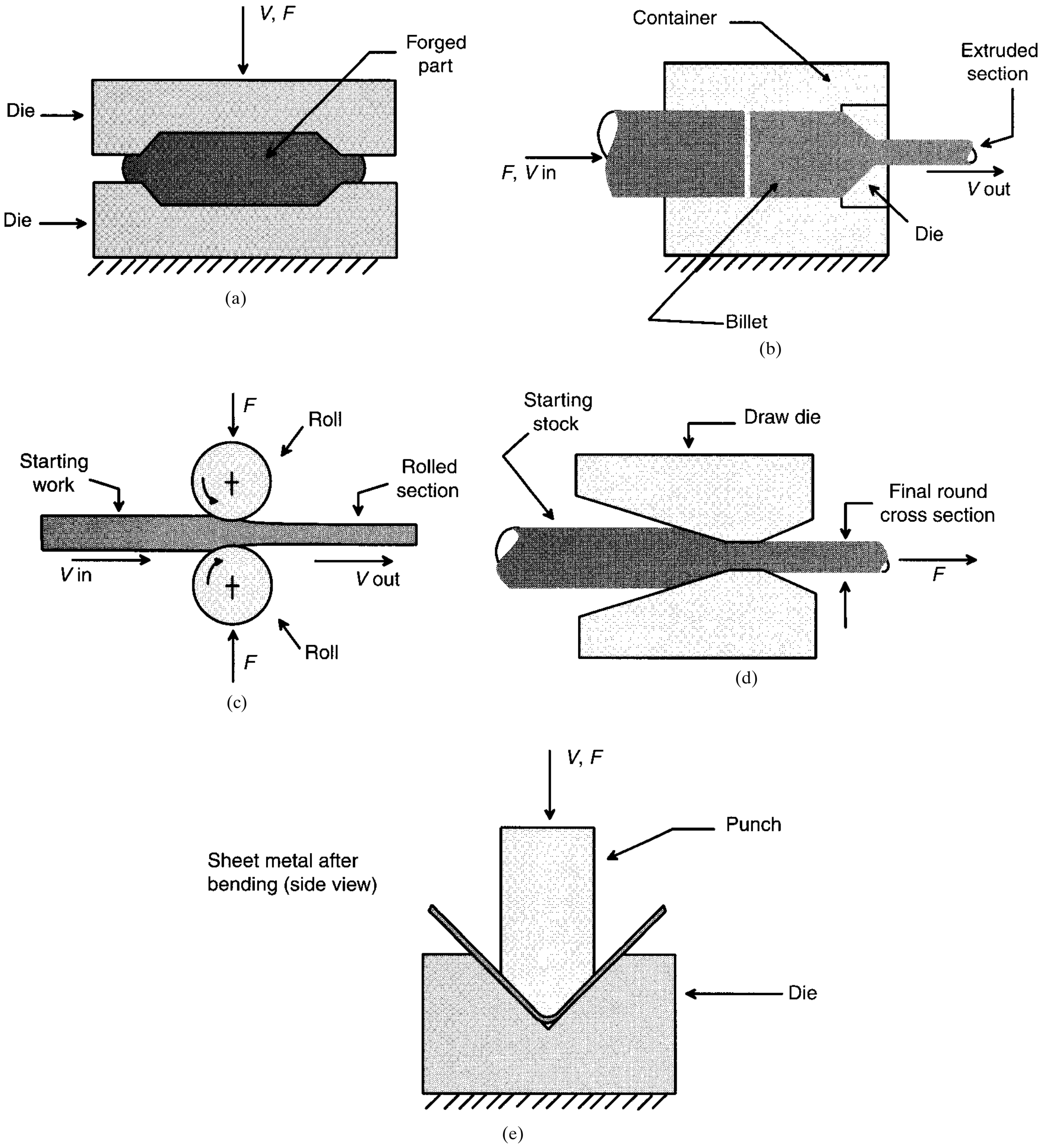
V, F
Forged part
Die
Die
(a)
Container
Extruded section
F, V in
V out
Die
Billet
(b)
F
Roll
Starting work
Rolled section
V in
V out
Roll
F
(c)
Starting stock
Draw die
Final round cross section
F
(d)
V, F
Punch
Sheet metal after bending (side view)
Die
(e)

FIGURE 14.1.5 Some common deformation processes: (*a*) *forging,* in which two halves of a die squeeze the workpart, causing it to assume the shape of the die cavity; (*b*) *extrusion,* in which a billet is forced to flow through a die orifice, thus taking the cross-section shape of the orifice; (*c*) *rolling,* in which a starting slab or billet is squeezed between two opposing rolls to reduce its thickness; (*d*) *bar drawing,* in which a billet is pulled through a die opening; and (*e*) *bending* of sheet metal. Symbols *V* and *F* indicate motion and applied force, respectively.

TABLE 14.1.5 Common Sheet-Metal Operations

Process	Description
Bending	Straining of flat sheet metal around a straight axis to produce a bent shape. The included angle of the bend is determined by the bending die.
Blanking	Cutting of sheet metal along a closed outline in one step to separate the piece (called the *blank*) from the surrounding stock.
Drawing	A flat metal sheet is placed over a die cavity, and a matching punch is used to force the metal into the opening, taking the shape of the cavity. The process is called *drawing* because the sheet is stretched (drawn) into the cavity.
Embossing	A forming operation used to create indentations in sheet metal. The indentations may be raised or indented letters and numbers, or strengthening ribs in the sheet.
Punching	Cutting of sheet metal along a closed outline in one step to create a hole in the surrounding stock (the removed material is called a *slug*). Technically the same as blanking.
Shearing	Cutting of sheet metal along a straight line between two cutting edges (*shears*).

TABLE 14.1.6 Machining Processes That Use a Hard Sharp Cutting Tool to Remove Material

Process	Description
Boring	A single-point tool removes material from the interior surface of a preexisting hole in a rotating workpiece. While the workpiece rotates, the tool slowly *feeds* in a direction parallel to the hole axis to enlarge its inside diameter.
Broaching	A multiple-tooth cutting tool (called a *broach*) is moved linearly in a direction parallel to its axis relative to the work. The teeth are designed so that each tooth removes more material than its predecessor in order to create the desired geometry. Commonly used to enlarge round holes into shapes other than round.
Drilling	A rotating tool (called a *drill bit*) with cutting edges on its tip is forced to feed into the workpiece in a direction parallel to the axis of the tool. The rotating and feeding action of the tool creates a round hole. The machine tool commonly used in drilling is a *drill press.*
Milling	A workpiece is slowly fed past a rotating multitooth cutter (of generally cylindrical shape) to remove material. The cutter axis is perpendicular to the direction of workpiece travel to create (usually) a flat surface. There are many forms of milling, making it a very versatile machining process, capable of creating a variety of geometries.
Planing	A workpiece is moved linearly past a single-point tool to create a flat surface. The tool is then moved laterally a short distance (*feed*) for the next stroke.
Sawing	A narrow slit is cut into the work by a cutting tool (called a *saw blade*) consisting of narrowly spaced teeth. Several forms of sawing are available.
Shaping	A single-point tool is moved linearly past the workpiece to create a flat surface. The workpiece is then moved laterally a short distance (*feed*) for the next stroke.
Turning	A single-point tool removes material from the exterior surface of a rotating cylindrical workpiece. The tool penetrates a certain distance below the surface (*depth of cut*) and slowly moves (*feeds*) in a direction parallel to the axis of rotation to create a cylindrical geometry. The machine tool commonly used in turning is a *lathe.*

MANUFACTURING PROCESSES

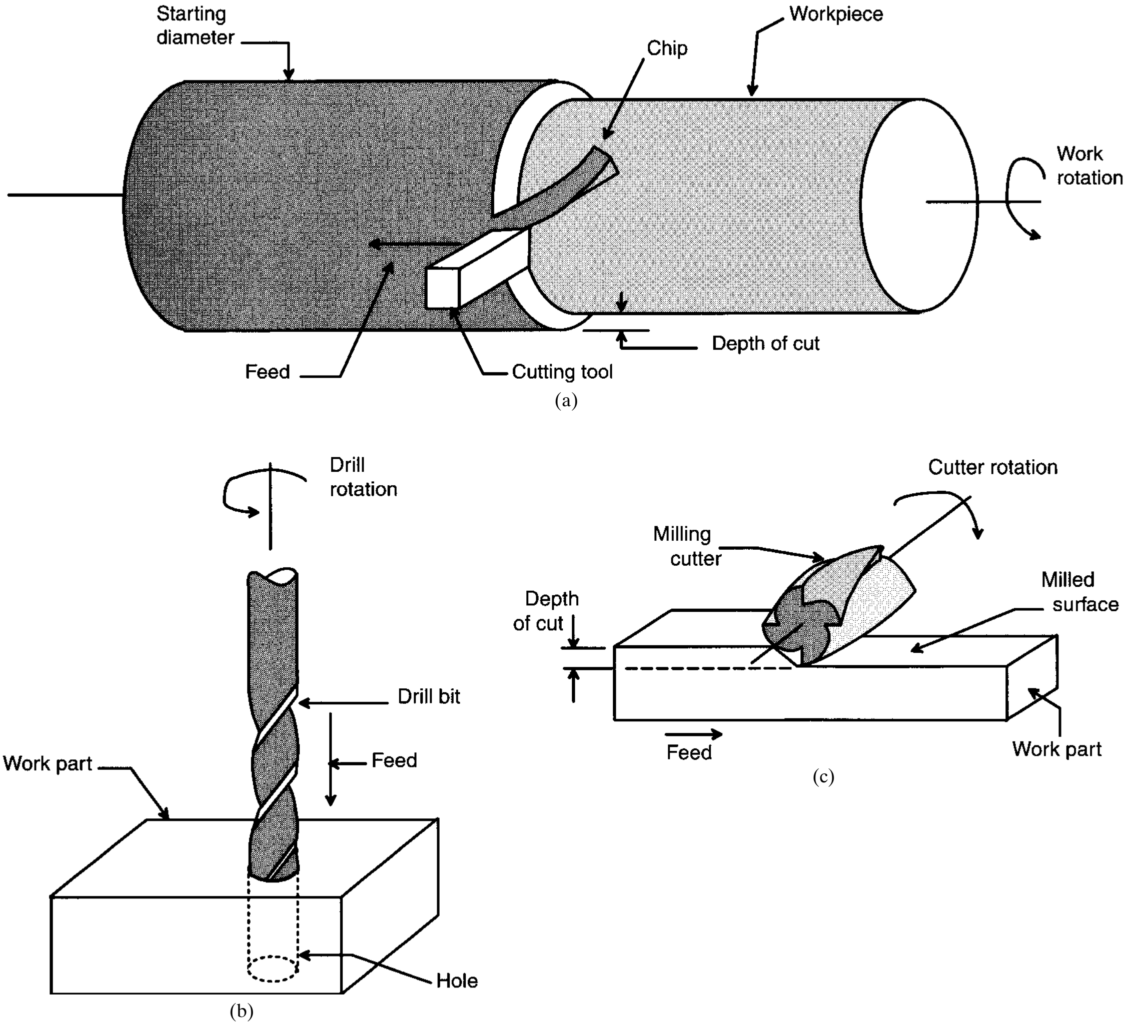
Starting diameter
Workpiece
Chip
Work rotation
Depth of cut
Feed
Cutting tool
(a)
Drill rotation
Drill bit
Feed
Work part
Hole
(b)
Cutter rotation
Milling cutter
Depth of cut
Milled surface
Feed
Work part
(c)

FIGURE 14.1.6 Common machining operations: (*a*) *turning,* in which a single-point cutting tool removes metal from a rotating workpiece to reduce its diameter; (*b*) *drilling,* in which a rotating drill bit is fed into the work to create a round hole; and (*c*) *milling,* in which a workpart is fed past a rotating cutter with multiple edges.

Some Closing Comments About Shaping Processes. It is desirable to minimize waste and scrap in converting a starting workpart into its subsequent geometry. Certain shaping processes are more efficient than others in terms of material conservation. Material removal processes (e.g., machining) tend to be wasteful of material, simply by the way they work—the material removed from the starting shape is waste. Other processes, such as certain casting and molding operations, often convert close to 100 percent of the starting material into the final product. Manufacturing processes that transform nearly all of the starting material into the product and require no subsequent machining to achieve final-part geometry are called *net-shape processes.* Other processes, such as forging, require minimum machining to produce the final shape and are called *near-net-shape processes.*

TABLE 14.1.7 Common Nontraditional Material Removal Processes

Process	Description
Abrasive water jet cutting (AWJC)	Similar to water jet cutting (see later) except that abrasive particles are introduced into the high-speed water stream to increase the cutting action.
Chemical machining (CHM)	Material removal is caused by a strong chemical etchant that chemically attacks the surface. Several types of CHM: **1.** *Chemical milling.* Used to remove metal from large flat sections such as aircraft panels **2.** *Chemical blanking.* Used to cut thin sheet-metal parts **3.** *Photochemical machining.* Uses a photoresist method of masking to determine areas to be cut
Electric-discharge machining (EDM)	Metal is removed by a series of discrete electrical discharges (sparks) that cause localized temperatures high enough to melt the metal in the immediate vicinity of the discharge. Work shape is determined by the shape of the electrode tool.
Electrochemical machining (ECM)	Removes material from an electrically conductive workpiece by anodic dissolution, the reverse of electroplating. Work shape is determined by the shape of the electrode tool.
Electron-beam machining (EBM)	Cutting is accomplished by a high-velocity stream of electrons focused on the surface. The electron beam removes material by melting and vaporization.
Laser-beam machining (LBM)	Use of a high-energy laser (light amplification by stimulated emission of radiation) focused on the surface. Material is cut by melting and vaporization.
Ultrasonic machining (USM)	Abrasives contained in slurry are forced at high velocity against the work surface by a high-frequency vibrating tool to remove material from the surface.
Water jet cutting (WJC)	Cutting is accomplished by a fine, high-pressure, high-velocity stream of water from a small nozzle orifice directed at the work surface. Used for cutting plastics, wood, textiles, floor tile, carpet, leather, and similar materials.
Wire EDM	Form of electric discharge cutting in which the electrode (cutting tool) is a thin wire, operating in a manner similar to a band saw.

TABLE 14.1.8 Some Common Heat Treating Operations

Process	Description
Annealing	Consists of: **1.** Heating a metal to a suitable temperature **2.** Holding at that temperature for a given time (called *soaking*) **3.** Slowly cooling Objectives: **1.** Reduce hardness and brittleness **2.** Improve formability and machinability **3.** Recrystallize strain-hardened metals **4.** Relieve residual stresses
Martensite formation in steel	Consists of: **1.** *Austenitizing.* The steel is heated sufficiently to convert to austenite. **2.** *Quenching.* The steel is cooled rapidly to avoid equilibrium transformation to ferrite and carbide, instead transforming to martensite, which has a similar structure as austenite but much harder and stronger.
Tempering of steel	Consists of: **1.** *Soaking* at a temperature below the eutectoid. **2.** *Slow cooling,* which follows soaking. It is applied to hardened steel to relieve stresses, reduce brittleness, and increase toughness.
Precipitation hardening	Also known as *age hardening,* it consists of: **1.** *Solution treatment.* Transforming the metal to a second phase **2.** *Quenching.* Creating a supersaturated solid solution **3.** *Precipitation treatment.* Heating the metal to cause precipitation of fine particles from solution that harden the metal. Applied to aluminum, copper, magnesium, and other nonferrous metals.
Surface hardening	Any of several thermochemical treatments of low-carbon steel in which the part surface composition is altered to cause hardening. Common treatments include: **1.** *Carburizing.* Carbon is added using heat and then quenching. **2.** *Nitriding.* Nitrogen is added.

Property-Enhancing Processes

The second major type of processing operation is performed to improve mechanical or physical properties of the work material. These processes do not alter the shape of the part, except unintentionally in some cases. The most important property-enhancing processes involve *heat treatments,* which include various annealing and strengthening processes for metals and glasses. Some of the common heat treating operations are identified in Table 14.1.8. *Sintering* of powdered metals and ceramics, mentioned earlier, is also a heat treatment that strengthens a pressed-powder metal workpart.

Surface-Processing Operations

These operations include cleaning, surface treatments, and coating and thin-film deposition processes. *Cleaning* includes both chemical and mechanical processes to remove dirt, oil, and other contaminants from the surface. *Surface treatments* include mechanical working such as shot peening and sand blasting, and physical processes like diffusion and ion implantation. *Coating* and *thin-film deposition* processes apply a coating of material to the exterior surface of the workpart.

Some of the common coating processes are defined in Table 14.1.9. Coating operations are most commonly applied to metal parts, less commonly to ceramics and polymers. In many cases, coatings are used on assemblies; for example, welded automobile bodies are painted and clear coated. There are a number of good reasons to apply coatings to the surface of a part or product: (1) corrosion protection, (2) color and appearance, (3) wear resistance, and (4) preparation for subsequent processing.

TABLE 14.1.9 Common Coating and Deposition Processes

Process	Description
Anodizing	An electrolytic process in which an oxide coating is formed on a metallic surface by chemical reaction. Unlike electroplating, the part is the anode in anodizing. Commonly used on aluminum.
Chemical vapor deposition (CVD)	Chemical reactions between a mixture of gases and the surface of a heated substrate, causing decomposition of some of the gas constituents and formation of a solid film on the substrate.
Electroless plating	A plating process driven entirely by chemical reactions, with no external source of electric current. Deposition occurs in an aqueous solution containing ions of the metal to be plated. The workpart serves as a catalyst for the plating reaction.
Electroplating	Also called *electrochemical plating,* this is an electrolytic process in which metal ions in an electrolyte solution are deposited onto a cathode part to form a thin coating. The anode is made of the metal being plated, and the cathode is the part. Commonly used on steel.
Hot dipping	This process consists of immersing a metal substrate in a molten bath of a second metal, which is coated onto the substrate upon removal.
Organic coating	Popularly known as *painting,* the process involves the application of a thin coating of polymer or resin liquids (usually, but powders are also used) that dry and harden on the surface of a substrate. Application methods include brushing, rolling, spraying, and immersion.
Phosphate coating	Formation of a phosphate film on a base metal surface by exposure to solutions of certain phosphate salts plus dilute phosphoric acid. Commonly used to prepare surface for painting.
Physical vapor deposition (PVD)	Conversion of a material into its vapor phase in a vacuum chamber and then condensing it onto a substrate as a very thin film. PVD can be used for a variety of coating materials (metals, alloys, ceramics, even some polymers) onto a variety of substrate materials (metals, glass, plastics).
Porcelain enameling	Process consists of: **1.** Preparation of the coating material as fine porcelain particles called *frit* **2.** Application onto the target surface by spraying, dipping, or other method **3.** Drying **4.** Firing to cause sintering of the porcelain powders
Thermal spraying	Molten coating materials are sprayed onto a substrate surface, solidifying and adhering to the surface.

Several surface-processing operations have been adapted to fabricate semiconductor materials into integrated circuits for microelectronics. These processes include *chemical vapor deposition, physical vapor deposition,* and *oxidation.* They are applied to very localized areas on the surface of a thin wafer of silicon (or other semiconductor material) to create the microscopic circuit.

ASSEMBLY OPERATIONS

The second basic type of manufacturing operation is *assembly,* in which two or more separate parts are joined to form a new entity. Components of the new entity are connected together either permanently or semipermanently. Permanent joining processes include welding, brazing, soldering, and adhesive bonding. They form a joint between components that cannot be easily disconnected. *Welding* is a materials-joining process in which two or more parts are coalesced at their contacting surfaces using a suitable application of heat and/or pressure. It is the most important process commercially. Welding divides into two major categories: (1) *fusion welding,* in which coalescence occurs by melting the two surfaces to be joined, in some cases adding a filler metal to the joint; and (2) *solid-state welding,* in which heat and/or pressure cause coalescence, but no melting of base metals occurs. Some of the common welding processes are defined in Table 14.1.10.

TABLE 14.1.10 Common Welding Processes

Process	Description
Arc welding (AW)	A family of fusion welding processes in which coalescence of the metals occurs using the heat of an electric arc between an electrode and the work. Electrodes in arc welding are either **1.** *Consumable.* Meaning they are consumed in the welding process and provide filler metal to the weld joint. **2.** *Nonconsumable.* Meaning the electrodes resist melting and therefore do not add metal to the weld joint.
Diffusion welding (DFW)	A solid-state welding process caused by the application of heat and pressure, usually in a controlled atmosphere, and allowing sufficient time for diffusion and coalescence to occur.
Electron-beam welding (EBW)	A fusion welding process in which heat for coalescence is generated by a highly focused stream of electrons impinging on the joint surface to be welded.
Explosion welding (EXW)	A solid-state welding process in which very rapid coalescence is achieved between the two surfaces using the energy of an explosive charge.
Friction welding (FRW)	A solid-state welding process in which coalescence is achieved by the heat of friction, induced by mechanical rubbing between the surfaces, combined with pressure.
Laser-beam welding (LBW)	A fusion welding process in which heat for coalescence is generated by a highly concentrated coherent light beam focused on the joint surface to be welded.
Oxyfuel gas welding (OFW)	A group of fusion welding processes in which the heat for coalescence is generated by burning various fuel gases. Gases commonly used in OFW include acetylene, propane, and methylacetylene-propadiene (abbreviated MAPP).
Resistance welding (RW)	Family of fusion welding processes that use a combination of heat and pressure to achieve coalescence of the two surfaces to be joined. The heat is generated by electrical resistance to current flow at the junction to be welded. The most common RW process is *resistance spot welding* (RSW), or simply *spot welding.*
Thermit welding (TW)	A fusion welding process in which heat for coalescence is generated by the superheated molten metal caused by chemical reaction of *thermite,* a mixture of aluminum and iron oxide that produces an exothermic reaction when ignited.
Ultrasonic welding (USW)	A solid-state welding process in which two parts are held together under moderate pressure, and oscillatory shear stresses of ultrasonic frequency are applied to the interface to coalesce the surfaces.

TABLE 14.1.11 Mechanical Assembly Methods

Process or hardware	Description
Cotter pins	Unthreaded fasteners formed from half-round wire into a single-stemmed pin. When inserted into holes of mating parts, the two legs of the pin are spread apart to hold the parts together.
Expansion fitting	Creating an interference fit between internal and external parts (e.g., a shaft in a hole) by cooling the internal part to shrink it by thermal contraction and then assembling the two parts. The internal part warms and expands to form the interference fit.
Press fitting	Forcing one component (e.g., a shaft of a certain diameter) into a matching component of a slightly smaller dimension (e.g., a hole of slightly smaller diameter) so that an interference fit occurs between the mating parts.
Rivets	Unthreaded, headed pins used for joining two parts by passing the rivet through holes in the parts and then forming a head on the opposite end of the pin. The forming process is called *upsetting*.
Shrink fitting	Creating an interference fit between internal and external parts (e.g., a shaft in a hole) by heating the external part to enlarge it by thermal expansion and then assembling the two parts. The external part cools and shrinks to form the interference fit.
Snap fitting	Assembly operation in which mating geometries of the two parts possess a temporary mechanical interference while they are being pressed together, which converts to mechanical interlocking once they are finally seated.
Threaded fasteners	Discrete hardware components having external or internal threads for assembly. Common threaded fasteners include *screws* and *bolts* (external threads) and *nuts* (internal threads). The external threads of one fastener (e.g., bolt) match the internal threads of a mating fastener (e.g., nut) of a part.

Brazing is a joining process in which a filler metal is melted and distributed by capillary action between two surfaces of the metal parts being joined. *Soldering* can be defined in the same terms, the difference being that the filler metal in brazing melts at a temperature above 450°C (840°F), whereas in soldering, the filler metal melts at a temperature below this level. *Adhesive bonding* is a joining process in which a filler material (the adhesive, usually a polymer) is used to hold two (or more) closely spaced parts together by surface attachment.

Mechanical assembly methods are available to fasten two (or more) parts together in a joint that can be conveniently disassembled. The use of screws, bolts, nuts, and other threaded fasteners are important traditional methods in this category. Other mechanical assembly techniques that form a more permanent connection include rivets, press fitting, and expansion fits. These mechanical fastening methods are defined in Table 14.1.11.

Special assembly methods are used in electronics. Some of the methods are identical to or adaptations of the aforementioned techniques. For example, soldering is widely used in electronics assembly. Electronics assembly is concerned primarily with the assembly of components (e.g., integrated circuit packages) to printed circuit boards to produce the complex circuits used in so many of today's products.

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BIOGRAPHY

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Source: MAYNARD'S INDUSTRIAL ENGINEERING HANDBOOK

CHAPTER 14.2

PROCESS DESIGN AND PLANNING

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Manufacturing instructions used to be scarcely more than "make to print." Today, complex manufacturing information handling systems have evolved to define in detail the complete manufacturing and assembly process to ensure that the design intent is properly executed during the production process. This is achieved by CAPP systems for process plan definition and MES for shop floor management. This chapter defines the evolution and implementation of CAPP systems.

HISTORY AND EVOLUTION OF PROCESS DESIGN AND PLANNING

Why Process Design and Planning?

The next time that you are in an airplane hurtling down the runway, you might consider the importance of the fact that someone developed detailed aircraft designs and that the manufacturing of this complex product followed the designs' intent.

A commercial airplane can have anywhere from 2,000,000 to nearly 3,500,000 parts, and virtually every airplane is unique. It is an extremely complex product, well beyond the capabilities of a single craftsperson or even a group of craftspersons.

The complexity of many of today's products and systems demand very detailed designs and—just as important, if not more so—the accurate translation of these designs to carry them through manufacturing and turn them into finished products. Detailed plans are needed to describe how individual parts should be made, how they should be combined in subassemblies, and then how the final product should be assembled.

In addition to the increasing complexity of products, manufacturing enterprises have to manage with fewer skilled and experienced craftspersons available to work on the shop floor, and when they are available, they are expensive. This has led to a decline in the skills of the people who perform the actual manufacturing and assembly. To compensate for this decline in skills and experience, even more detailed instructions are needed.

The methodology used to translate the engineering office's design intent into a manufacturable and workable product is process design and planning. The process plan is developed, then delivered, with related documentation, to the shop floor. Done properly, the planning package enables the workers on the shop floor to produce a product that accurately incorporates the design intent.

Evolution of Process Design and Planning

Through most of the history of manufacturing technology, blueprints or other types of drawings were prepared and released directly to the shop floor. Process design and planning consisted of a "make fit to print" notation on the drawing—machinists on the shop floor were instructed to create what was shown in the drawing. Exactly how they did so was up to them.

This approach was virtually universal as late as the 1930s, and remained commonplace through the 1940s. It is still not unusual in some very small companies and, under certain circumstances, in large companies as well. In the automotive industry, for example, when some types of functionalities are not properly installed on a car delivered from the assembly area, skilled car mechanics will take the car off the line and repair what was wrong or make needed improvements before the car is delivered to the customer.

The "make fit to print" approach may have worked reasonably well in simpler times, but it is not the best way to do business in today's world. It takes an extraordinarily skilled craftsperson to manufacture a part well by just looking at a drawing, no matter how detailed the drawing might be. And even in the best of circumstances, there were likely to be substantial differences between pieces made from the same print by different machinists. While the differences might not be serious in a buggy spring, they could lead to disaster in a set of jet engine turbine blades. And since the methodology was in the maker's head, and not in any kind of document, recordkeeping was minimal or nonexistent. When machinists retired, died, or left the company for any reason, all their experience and know-how went with them.

The "make fit to print" approach was expensive, led to inconsistencies in production, and made it impossible to take advantage of experience on any large scale. Obviously, a more formal approach was needed to achieve economies, raise quality levels, and standardize—and optimize—manufacturing methods.

The Written Process Plan. The next step in the evolution of modern batch manufacturing was the introduction of written process planning documents, accompanied by organizational changes that facilitated their preparation.

Instead of releasing drawings directly to the shop floor, design engineers now sent their output to a new type of office that stood between design and manufacturing: the manufacturing engineering department. Manufacturing engineering department personnel, often called *process planners,* were usually people with extensive shop floor experience, people who knew and understood manufacturing operations and the machines available in the company. They produced handwritten documents that contained detailed instructions for each of the operations required to manufacture each part, and then released these documents, including the drawings, to the shop floor. Shop floor personnel then followed these instructions as the part moved through the manufacturing process. This procedure is still followed in many smaller manufacturing environments, not only in the United States but also throughout the world.

While the first written process plans were probably pretty simple documents, they became more sophisticated with time. For example, a lot of the quality of a given process plan depended on the process planner's experience and ability to recall and reuse their best ways of doing things—standardized approaches to various operation situations. As copying machines became more common, the handwritten documents began to include copies of best method sections of older plans, cut and pasted into the new plan where appropriate. Furthermore, these handwritten plans were, on many occasions, embellished with sketches that illustrated how to do particular setups or operations, as supporting information for the persons who were going to do the work.

The Electronic Pencil. The introduction of computerized systems into manufacturing engineering led to the next step in the evolution of written process planning documentation: the introduction of what might be called the *electronic pencil* (word processing).

Instead of handwriting and cut-and-paste copies, electronic pencil documentation was produced with computers—first minicomputers and then, as they became available, personal computers. Off-the-shelf word processing or spreadsheet programs provided the tools to create, store, and sometimes retrieve planning documents.

For companies making generally simple products, with a limited number of relatively uncomplicated tools and operations, the electronic pencil approach still has a number of advantages. This has become increasingly true as word processors and spreadsheet programs have added capabilities. Today, they can contain forms, graphics, photographs, and even video along with the traditional text.

While the electronic pencil has proven to be very useful in many straightforward manufacturing environments, it has restrictions that make it less useful in more complex situations. While some retrieval is possible, capabilities for the intelligent retrieval of previous experience are limited. It is also difficult, if not impossible, to link such systems with other types of existing in-house systems, such as product data management systems, material requirement planning systems, mainframe financial information systems, and so forth.

Retrieval Capabilities. The next chapter in the history of manufacturing process and planning documentation was the development of an electronic pencil approach that had retrieval capabilities. It marked the departure from the use of derivatives of standard consumer-market software; it was designed and written specifically for process planning applications.

To fill the needs of manufacturing engineers, it had electronic pencil features and the ability to retrieve previous company manufacturing experience by a variety of different keys. For example, using the part number or part name as the key, one could retrieve the author of a process plan, the function of the part, or even analyze similarities of different parts being made in the factory and look for families of parts that could employ standard plans.

The retrieval of standardized operation descriptions was another important capability. Blocks of standard text, with detailed instructions for specific operations on individual machine tools, could be stored in the system. These instructions could be easily retrieved and included in process plans as is, or modified if and when necessary.

The introduction of relational database management systems made these capabilities very powerful. It became easier to search for combinations of similarities based on a wide range of keys. It was further possible to group parts with manufacturing similarities into families that could be manufactured in machine cells. Many companies are using the identification of similarities on some level, although not always with a complete analysis of all manufacturing similarities. The grouping of parts, which are similar from a design or manufacturing point of view, is often called *group technology*.

The electronic pencil with retrieval type of process planning system is widely used and has been very successful in companies that make parts of medium complexity.

Linking to Other Systems. The next rung up the evolutionary ladder is occupied by process design and planning systems that combine electronic pencil and retrieval capabilities with the ability to link to other enterprise systems. These are the modern computer-aided process planning (CAPP) systems of today. They tend to be purpose written, either by in-house personnel, or by suppliers specializing in manufacturing software systems. In addition to word processing and internal relational database retrieval functionalities, they also can retrieve data from other in-house systems or databases. For example, they may be able to draw computer graphics images from existing computer-aided design (CAD) systems, they may be linked to product data management systems for configuration control, and they may supply information to manufacturing or enterprise resource planning (MRP/ERP) systems. They may be part of a larger manufacturing engineering office that also handles tool planning and tool inventory control.

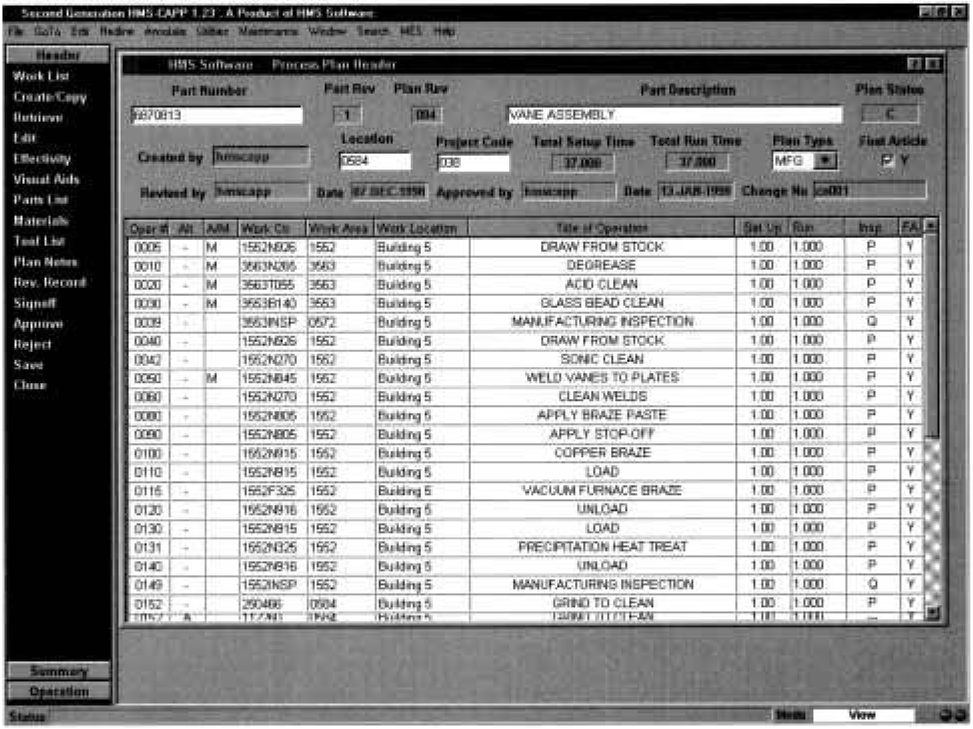
They may also have state-of-the-art communication capabilities so that they can distribute detailed work instructions to the shop floor with text, graphics, videos, and photographs—

available in hard copies or on shop floor terminal screens, including feedback from the shop floor and data collection (manufacturing execution systems [MES]).

Today's Leading Edge Systems. The advanced CAPP systems of today are complete purpose-written systems. In terms of functionality, they are integrated manufacturing information–handling systems. They offer all the capabilities described previously, including the ability to deliver planning documentation in combinations of text, graphics, photographs, videos, and voice. Typically they are running in client/server environments using relational database systems. Their far-reaching functionality often puts them in the center of a web of different manufacturing activities; they are now integrated with other manufacturing information systems such as ERP/MRP and MES systems. For example, one advanced computer-aided process planning system is linked to more than 60 different monitoring systems in a large aircraft company.

The linkages to other systems are often driven by the need to have detailed records that not only include designs, but also contain accurate data about manufacturing and assembly planning and execution. Such detailed and comprehensive record keeping is required to satisfy the needs of modern-day quality systems such as ISO 9000.

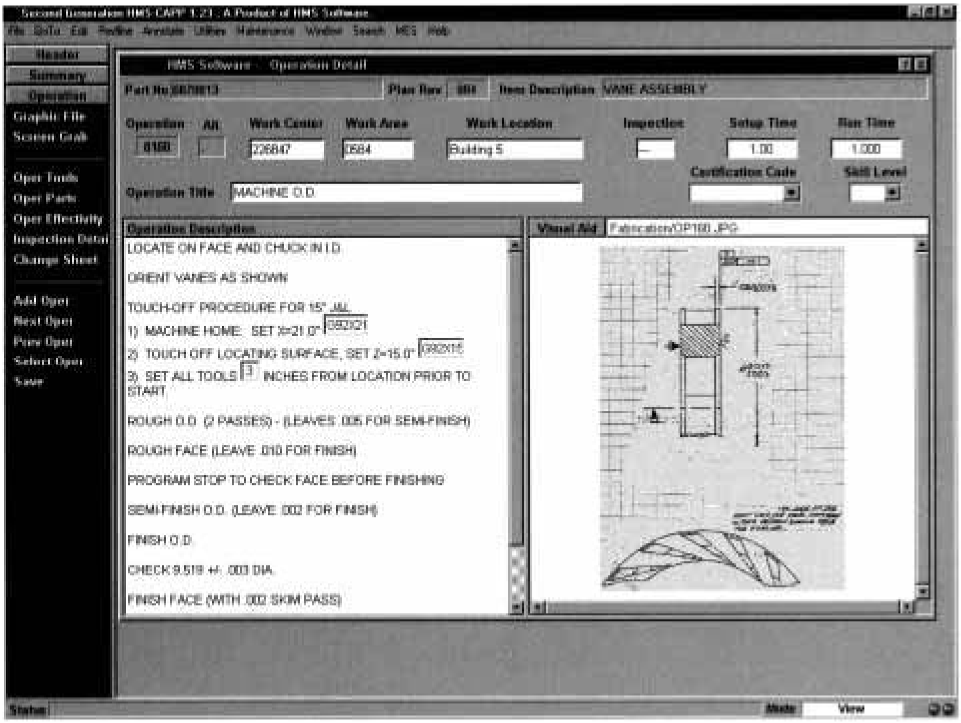
While such advanced CAPP systems may be expensive, their return on investment is extraordinarily high. By improving the flow of information to the shop floor, they make considerable contributions to improvements in quality. Furthermore, their ability to retrieve and use best production methods generates significant increases in manufacturing efficiencies, with less scrap and rework, and shorter throughput times. As a result, it is not uncommon to see paybacks, including hardware costs, in two to three years. An example of a process plan with several detail sheets, generated by an advanced CAPP system, is shown in Fig. 14.2.1.



Part Number: 6870813
Part Rev: 1
Plan Rev: 004
Part Description: VANE ASSEMBLY
Plan Status: C
Created by: hmscapp
Location: 0584
Project Code: 038
Total Setup Time: 37.000
Total Run Time: 37.000
Plan Type: MFG
First Article: ☑ Y
Revised by: hmscapp
Date: 07-DEC-1998
Approved by: hmscapp
Date: 13-JAN-1999
Change No: ca001

Oper #	Alt	A/M	Work Ctr	Work Area	Work Location	Title of Operation	Set Up	Run	Insp	FA
0005	-	M	1552N026	1552	Building 5	DRAW FROM STOCK	1.00	1.000	P	Y
0010	-	M	3563N285	3563	Building 5	DEGREASE	1.00	1.000	P	Y
0020	-	M	3563T055	3563	Building 5	ACID CLEAN	1.00	1.000	P	Y
0030	-	M	3563B140	3563	Building 5	GLASS BEAD CLEAN	1.00	1.000	P	Y
0039	-		3563INSP	0572	Building 5	MANUFACTURING INSPECTION	1.00	1.000	Q	Y
0040	-		1552N826	1552	Building 5	DRAW FROM STOCK	1.00	1.000	P	Y
0042	-		1552N270	1552	Building 5	SONIC CLEAN	1.00	1.000	P	Y
0050	-	M	1552N845	1552	Building 5	WELD VANES TO PLATES	1.00	1.000	P	Y
0060	-		1552N270	1552	Building 5	CLEAN WELDS	1.00	1.000	P	Y
0080	-		1552N806	1552	Building 5	APPLY BRAZE PASTE	1.00	1.000	P	Y
0090	-		1552N805	1552	Building 5	APPLY STOP-OFF	1.00	1.000	P	Y
0100	-		1552N815	1552	Building 5	COPPER BRAZE	1.00	1.000	P	Y
0110	-		1552N815	1552	Building 5	LOAD	1.00	1.000	P	Y
0115	-		1552F325	1552	Building 5	VACUUM FURNACE BRAZE	1.00	1.000	P	Y
0120	-		1552N816	1552	Building 5	UNLOAD	1.00	1.000	P	Y
0130	-		1552N815	1552	Building 5	LOAD	1.00	1.000	P	Y
0131	-		1552N325	1552	Building 5	PRECIPITATION HEAT TREAT	1.00	1.000	P	Y
0140	-		1552N816	1552	Building 5	UNLOAD	1.00	1.000	P	Y
0149	-		1552INSP	1552	Building 5	MANUFACTURING INSPECTION	1.00	1.000	Q	Y
0152	-		250466	0584	Building 5	GRIND TO CLEAN	1.00	1.000	P	Y

FIGURE 14.2.1 Example process plan header and detail sheets.


Second Generation HMS-CAPP 1.23 - A Product of HMS Software
HMS Software - Operation Detail
Header
Summary
Operation
Graphic File
Screen Grab
Oper Tools
Oper Parts
Oper Effectivity
Inspection Detail
Change Sheet
Add Oper
Next Oper
Prev Oper
Select Oper
Save
Status
Mode
View

Part No [illegible] Plan Rev [illegible] Item Description VANE ASSEMBLY

Operation	Alt	Work Center	Work Area	Work Location	Inspection	Setup Time	Run Time
0160		226847	0684	Building 5	—	1.00	1.000

Operation Title MACHINE O.D.

Certification Code

Skill Level

Visual Aid Fabrication/OP160.JPG

Operation Description

LOCATE ON FACE AND CHUCK IN I.D.

ORIENT VANES AS SHOWN

TOUCH-OFF PROCEDURE FOR 15" JAL

1) MACHINE HOME. SET X=21.0" 0382X21

2) TOUCH OFF LOCATING SURFACE, SET Z=15.0" 0382X15

3) SET ALL TOOLS 3 INCHES FROM LOCATION PRIOR TO START

ROUGH O.D. (2 PASSES) - (LEAVES .005 FOR SEMI-FINISH)

ROUGH FACE (LEAVE .010 FOR FINISH)

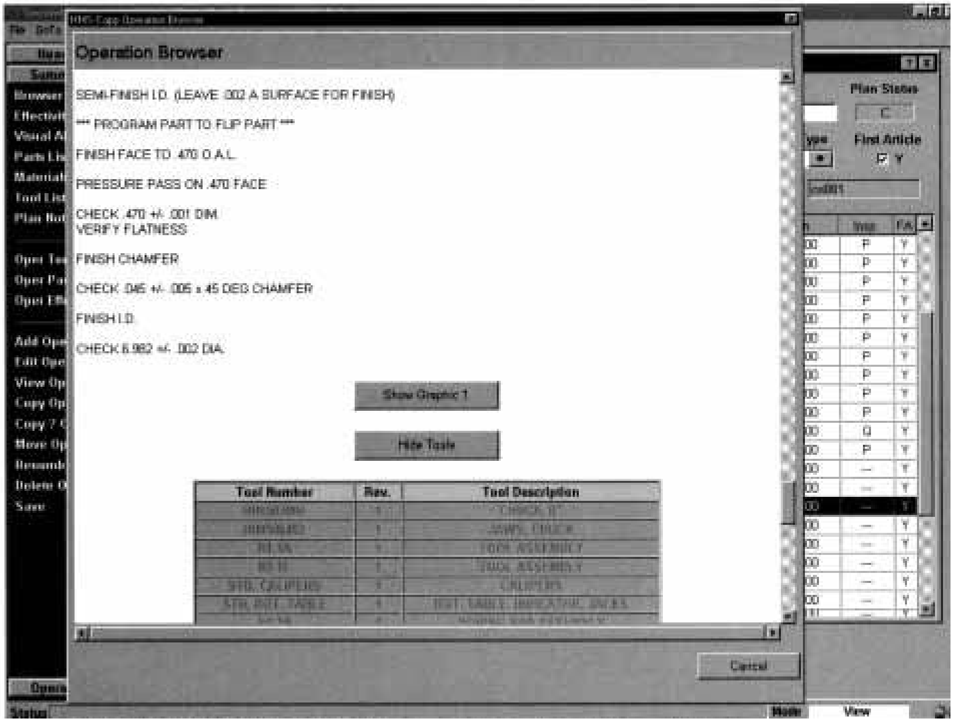
PROGRAM STOP TO CHECK FACE BEFORE FINISHING

SEMI-FINISH O.D. (LEAVE .002 FOR FINISH)

FINISH O.D.

CHECK 9.519 +/- .003 DIA.

FINISH FACE (WITH .002 SKIM PASS)


HMS-Capp Operation Browser
Operation Browser
Browser
Effectivity
Visual Aid
Parts List
Materials
Tool List
Plan Notes
Add Oper
Edit Oper
View Oper
Copy Oper
Move Oper
Renumber
Delete Oper
Save
Plan Status
First Article
Show Graphic 1
Hide Tools
Cancel
Status
Mode
View

SEMI-FINISH I.D. (LEAVE .002 A SURFACE FOR FINISH)

*** PROGRAM PART TO FLIP PART ***

FINISH FACE TO .470 O.A.L.

PRESSURE PASS ON .470 FACE

CHECK .470 +/- .001 DIM.
VERIFY FLATNESS

FINISH CHAMFER

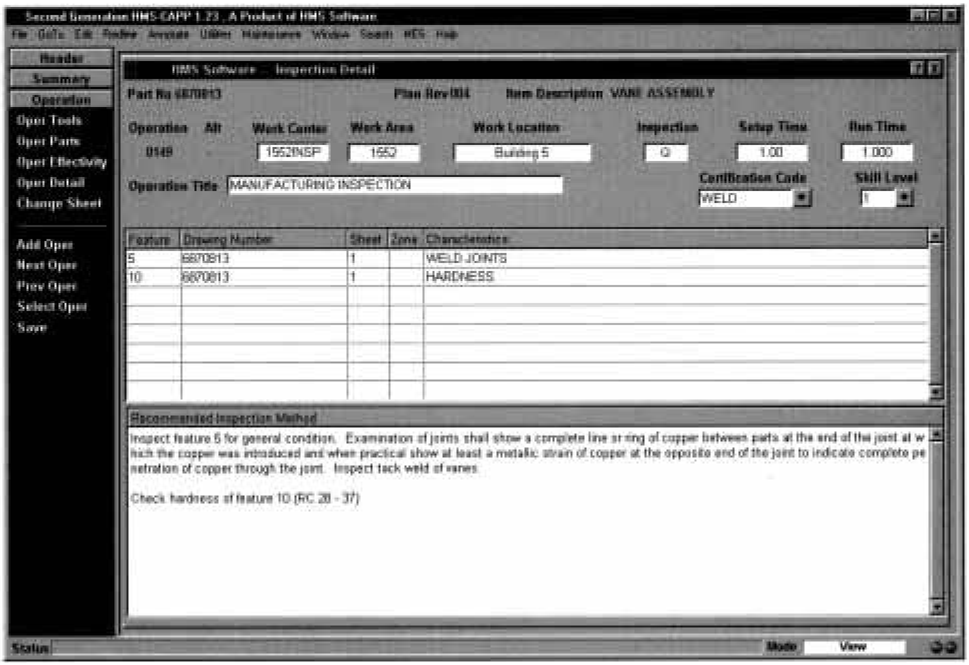
CHECK .045 +/- .005 x 45 DEG CHAMFER

FINISH I.D.

CHECK 6.982 +/- .002 DIA.

Tool Number	Rev.	Tool Description
[illegible]	1	[illegible]
[illegible]	1	JAWS, CHUCK
[illegible]	1	TOOL ASSEMBLY
[illegible]	1	TOOL ASSEMBLY
STD. CALIPERS	1	CALIPERS
[illegible]	1	[illegible]

FIGURE 14.2.1 *(Continued)*


Second Generation HMS-CAPP 1.23 , A Product of HMS Software
File GoTo Edit Redline Annotate Utilities Maintenance Window Search MES Help
Header
Summary
Operation
Oper Tools
Oper Parts
Oper Effectivity
Oper Detail
Change Sheet
Add Oper
Next Oper
Prev Oper
Select Oper
Save
HMS Software – Inspection Detail
Status
Mode

Part No 6870813 Plan Rev 004 Item Description VANE ASSEMBLY

Operation	Alt	Work Center	Work Area	Work Location	Inspection	Setup Time	Run Time
0149	-	1552INSP	1552	Building 5	Q	1.00	1.000

Operation Title: MANUFACTURING INSPECTION

Certification Code: WELD

Skill Level: 1

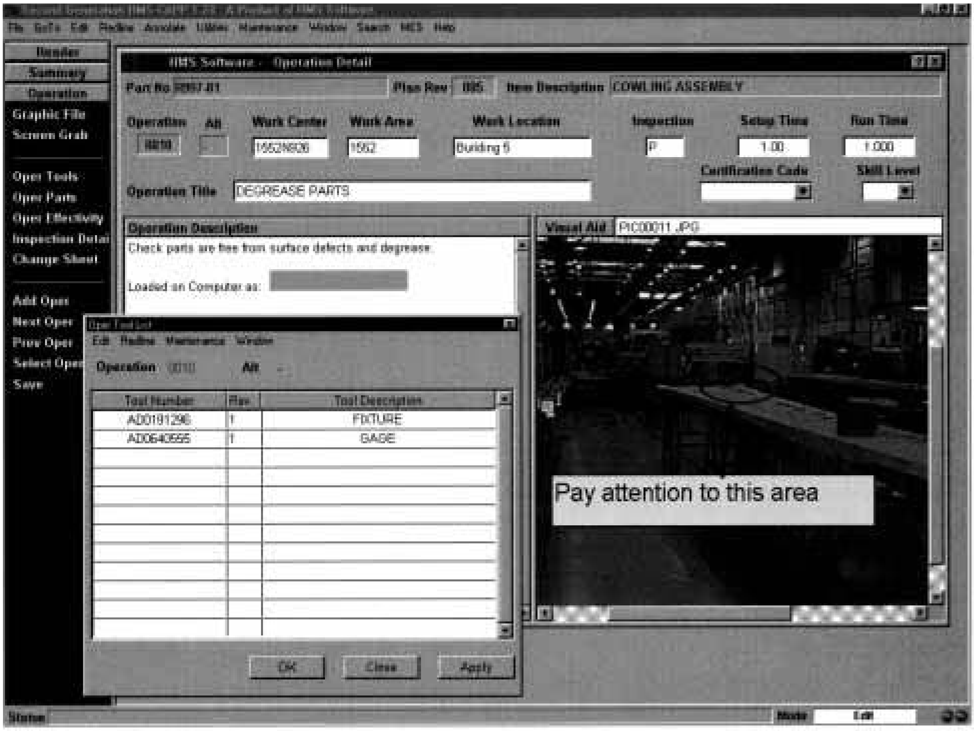
Feature	Drawing Number	Sheet	Zone	Characteristics
5	6870813	1		WELD JOINTS
10	6870813	1		HARDNESS

Recommended Inspection Method

Inspect feature 5 for general condition. Examination of joints shall show a complete line or ring of copper between parts at the end of the joint at which the copper was introduced and when practical show at least a metallic strain of copper at the opposite end of the joint to indicate complete penetration of copper through the joint. Inspect tack weld of vanes.

Check hardness of feature 10 (RC 28 - 37)

Mode: View


Second Generation HMS-CAPP 1.23 , A Product of HMS Software
File GoTo Edit Redline Annotate Utilities Maintenance Window Search MES Help
Header
Summary
Operation
Graphic File
Screen Grab
Oper Tools
Oper Parts
Oper Effectivity
Inspection Detail
Change Sheet
Add Oper
Next Oper
Prev Oper
Select Oper
Save
HMS Software – Operation Detail
Oper Tool List
Edit Redline Maintenance Window
OK
Close
Apply
Pay attention to this area
Status
Mode

Part No [illegible] Plan Rev 005 Item Description COWLING ASSEMBLY

Operation	Alt	Work Center	Work Area	Work Location	Inspection	Setup Time	Run Time
0010	-	1552N806	1552	Building 5	P	1.00	1.000

Operation Title: DEGREASE PARTS

Certification Code:

Skill Level:

Operation Description

Check parts are free from surface defects and degrease.

Loaded on Computer as:

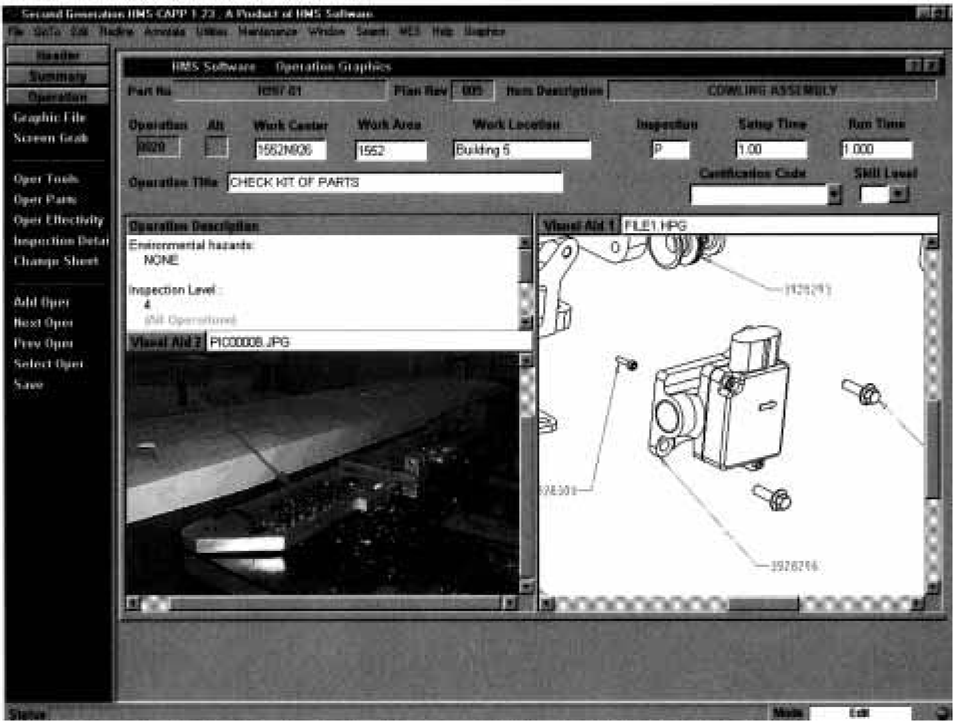
Visual Aid: PIC00011.JPG

Operation 0010 Alt -

Tool Number	Rev	Tool Description
AD0191296	1	FIXTURE
AD0640565	1	GAGE

Mode: Edit

FIGURE 14.2.1 (*Continued*)


Second Generation HMS-CAPP 1.23 - A Product of HMS Software
File GoTo Edit Redline Annotate Utilities Maintenance Window Search MES Help Graphics
Header
Summary
Operation
Graphic File
Screen Grab
Oper Tools
Oper Parts
Oper Effectivity
Inspection Detai
Change Sheet
Add Oper
Next Oper
Prev Oper
Select Oper
Save
HMS Software - Operation Graphics
Status
Mode
Edit

Part No 1097-01 Plan Rev 005 Item Description COWLING ASSEMBLY

Operation 0020 Alt

Work Center 1552N926

Work Area 1552

Work Location Building 5

Inspection P

Setup Time 1.00

Run Time 1.000

Operation Title CHECK KIT OF PARTS

Certification Code

Skill Level

Operation Description

Environmental hazards:
NONE

Inspection Level :
4
(All Operations)

Visual Aid 1 FILE1.HPG

Visual Aid 2 PIC00008.JPG

FIGURE 14.2.1 (*Continued*)

MASS PRODUCTION AND LOW QUANTITY PRODUCTION

To the average observer, it may appear easy to tell the difference between mass production and discrete—small lot size—production. Mass production conjures up images of long assembly lines producing thousands of copies of the same product; low-quantity production (discrete production) is an aircraft plant that turns out one airplane at a time.

Between those two extremes, however, is a middle ground where one may speak about discrete manufacturing with lot sizes of 10,000 or more, produced on universal machine tools, or of mass production series that may be much smaller. To fully understand the roles of process design and planning in different manufacturing environments, we need to understand the differences between mass production and discrete production.

Aspects of Mass Production

Generally speaking, mass production is based on sales forecasts, on the expectation that large numbers of products will be sold. These products are not shipped immediately to customers; they are made to supply inventories that will be drawn on as sales are made. For the most part, they are consumer products, things like automobiles, kitchen appliances, and consumer electronics.

In a mass production environment, products are developed jointly by design engineers and manufacturing engineers. The design engineers are concerned about aesthetics, functionality, and other user-oriented matters, while the manufacturing engineers focus on manufacturability, ease of assembly, and other production issues.

Manufacturing is accomplished on assembly lines where specific people have predetermined tasks to be done in a particular time (cycle time). On many assembly lines, highly specialized equipment and robots are used to perform specific tasks, usually built and/or programmed to conform to the requirements of the model or models currently in production. These specialized machines are expensive and often cannot be used for other purposes. Heavy investments in specialized equipment, robots, and integrated engineering/manufacturing teams are acceptable; however, because their costs can be amortized over very large lot sizes, often of 100,000 and more. Typical workers' tasks are relatively easy to learn and perform because of their limited scope. There is no need to look at a process document for every part or assembly that passes through their station. It is always the same operation on the same part.

Discrete Production Characteristics

In a discrete manufacturing environment, production is generally driven by actual orders and, as a consequence, by their delivery schedules. Most products in this category tend to be for business, defense, and industrial customers: industrial equipment, aircraft, steam turbines, and many types of heavy equipment. A lot size may be as small as one, or as large as several thousand. Whatever the number, the point is that each worker performs specialized operations on each unit in the lot and when finished may start a different job with different specifics and probably a different lot size. Each lot is likely to be different from the one that precedes or follows it, and often using universal machine tools, the worker's tasks are also different. Thus, every job for every lot must be accompanied by detailed work instructions that have to be followed to the letter. Furthermore, the work has to be checked and signed off when it is finished.

Much more individual craftsmanship is required from shop floor machinists than from assembly line workers. For the most part, they must be able to perform a variety of different tasks on general-purpose machine tools that are either manually operated or numerically controlled. The exact nature of their tasks varies with each lot, depending on the requirements of the particular part that is being made.

Since finished products are usually an assembly of individual parts, most mass production is carried out on assembly lines. The individual tasks are repetitive, repeating in a matter of seconds or, at most, minutes. In a discrete production environment, teams of workers combine to finish the product, and the typical assembly time for a discrete production environment may be hours or even days. It can take many weeks to assemble an aircraft.

PROCESS DESIGN AND PLANNING FOR MASS PRODUCTION

Process design and planning for mass production is a complex process involving the design and utilization of highly specialized equipment, coordination of equipment suppliers, and a great deal more. A detailed description would be beyond the scope of this chapter. A mass production perspective is helpful in understanding the differences in discrete manufacturing, however, so the following is a brief overview.

Economic Issues

Because the lot sizes in mass production are so high, it is very important to recognize that small differences in unit costs can have big impacts on ultimate profitability. If a manufacturer can save 10¢ on a reflector used on a car, and makes 500,000 of those cars, the total savings are substantial.

For example, many years ago, the author met a manufacturing engineer who was responsible for the manufacturing process for making the lower cup of a telephone handset—only the lower cup. The engineer proudly announced that he had saved slightly more than .5¢ in the manufacture of these cups. When I reacted to his announcement with raised eyebrows, he reminded me that his company was making 10 million of these cups every year and that the total savings were thus in the tens of thousands of dollars!

In the mass production world, integrated teams are created to conceive the product. A team may include sales and marketing personnel, design engineers, production personnel, and others with interests in how the product will be made, distributed, and sold. The teams will define the design intent of the product, driven by anticipated market issues and sales forecasts.

Design Objectives

The key question facing these integrated teams is how to design a product with an overall manufacturing and assembly process that will cost as little as possible while ensuring that intended quality objectives are met. What new manufacturing technologies can be introduced to make the product more useful, or cheaper to make? How easy is it to manufacture a given part or assembly? How easy is it to assemble the final product? And to repair it, if and when needed?

It is interesting to note that a by-product of the work of these integrated teams is that mass-produced products often contain fewer, more complex parts than their batch-manufactured cousins.

Thanks to the large volumes involved, it is often more economical to construct a specialized machine to build a single complex part, instead of making several simpler parts on existing machine tools and bolting these together. The benefits are not only in cost savings but also in higher quality.

When making a single complex part, one has to deal with only a single set of outside tolerances. Because of the prohibitive costs of creating special machines for small runs, in discrete environments, the same part would probably be constructed of a number of simple parts. It would be a complex subassembly, with tolerance—and thus quality—issues for every individual part it contained.

Another aspect of the integrated approach to mass production is that decisions have to be made to determine what part production will be contracted to suppliers and, in these days, even to integrate the supplier design team with design and manufacturing process responsibility. Configuration control of the final product is yet another important issue. In the course of the model year, new design and manufacturing changes are introduced in the product cycle. Product data management systems are available to keep track of final assembly configuration so that it is possible to identify and track all parts in each model and each model variation.

The Processes

Once the major designs and overall manufacturing processes have been defined for the assembled product, the real work starts for the manufacturing and process engineers. The immediate challenges are to work out the detailed processes, including where and how to use newly available technologies, to design and develop specifications for special machines and machine tools, and to establish and maintain effective communications with subcontractors.

The next challenge is to look at the complete manufacturing or assembly task, and to slice the totality up into detailed subtasks for the workers to be completed per production cycle. Assembly lines have to be balanced so that each worker on the line has approximately the same amount of work to do per cycle.

Once this has been accomplished, test manufacturing and assembly lines need to be set up to check whether it all works. When this is done, and the detailed processes have been checked and accepted, the process engineers' job is essentially finished.

It is then the responsibility of the "documentors" to describe the entire process in terms of individual worker tasks. The resulting process books are distributed at strategic places in the manufacturing shop or assembly environment as references for the workers who are actually going to do the work. Although they may be intended for instructing workers on the line, they are very rarely consulted; cycle times are tight and there is not enough time to look at the books.

There are other uses for these process books. For example, the detailed description of the making and assembling of a product is important to be able to track the source of quality problems should they arise. It is also an essential step in ISO 9000 certification.

PROCESS DESIGN AND PLANNING FOR DISCRETE MANUFACTURING

Dealing with Smaller Lot Sizes

Because of the much smaller lot sizes, discrete manufacturing does not normally accommodate an integrated design and manufacturing team that can optimize the production of designs with the best manufacturing technologies. A manufacturing engineering department is usually responsible for the process design in discrete environments. Contrary to mass production environments, where most process engineers have little or no hands-on shop floor experience, in discrete manufacturing most process planners start on the shop floor and then move to planning. The practical lessons learned in their early years provides them with an understanding of best practices for their specific manufacturing operation. Further, there is more feedback from the machine shop or assembly shop to the manufacturing engineering department than to the design department.

Normally, the design department releases a drawing reflecting the design intent and it is then up to the manufacturing engineering department to decide how to realize it. The manufacturing shop makes its contribution either through the process planner's experience and time spent on the shop floor discussing processes, or through organized feedback systems. For example, with redlining systems, suggested changes to existing process plans are sent from the shop floor to the manufacturing engineering office. Furthermore, to make sure that the design intent is realized with the company's best available technology, process plans that are designed in the manufacturing engineering department go through an extensive peer review and sign-off procedure.

Computer-Aided Process Planning Functionalities

Computer-aided process planning is a key system in medium- to large-scale manufacturing engineering offices. It is not only used for detailed parts, subassemblies, and final assemblies, but also for the planning of tools, jigs, and fixtures.

The design and layout of process plans differs from company to company. Variations may reflect practices prior to automation, or they may be based on other company practices, traditions, or information needs.

Most process plans consist of three to four principal sections. First, there is the header section. It may include the identification of materials used, part number, part name, name of the process planner, date, and other basic details. The second part is usually the summary of operations, sometimes also called the routing. It lists operations by number and contains a one-line summary description of each operation. It also includes the setup and run times, and, sometimes, the tools used. The third section usually contains more detailed descriptions of each of the operations listed and summarized in the second section. Often on separate pages, these operation sheets may contain text and graphics, photographs, video clips, or even voice information.

For the people on the shop floor, the operation description is the most important part of the process plan—it tells the individual exactly what to do and, in many ways, how to do it.

Some process plans have a fourth section, generally for more complex operations. It may provide very detailed instructions about individual steps that may be required in certain operations. Beyond that, the process plan may be accompanied by a tool order or product specifications, it may contain specifications about gluing, welding, and other nonmachining operations, and it may have separate sheets that deal with safety regulations and/or other regulatory or quality issues.

As a result, a modern process plan for a part or assembly of moderate complexity may include anywhere from 10 to more than 50 operations, and the entire planning document, including the header and the summary, may be as big as a book.

Manufacturing Engineering Change Management. Many CAPP systems have a functionality, sometimes called the manufacturing engineering change management module, that initiates work allocation. It essentially deals with how the parts or assemblies released from the engineering department will be scheduled through and out of the manufacturing engineering department, and it may include any engineering or manufacturing change orders. Used properly, it is almost like a manufacturing engineering management system to help ensure that workers use the process planning system in the proper way.

Once the workload has been distributed through the manufacturing engineering change management system, the next activity is the generation of a manufacturing bill of material. The engineering bill of material (E-BOM) created in the engineering department has to be converted to a manufacturing bill of material (M-BOM). While the E-BOM may consider parts according to their functions, the M-BOM regard them as they will be manufactured, subassembled, and assembled. The M-BOM may be physically located in the manufacturing engineering process planning database or in the product data management (PDM) system, depending on company philosophy about the border between PDM and manufacturing engineering.

Planner's Work List. Using data from the manufacturing engineering change management system, the next level of a computer-aided process planning system is a process planner's work list. When a process planner comes to work in the morning, he or she starts up the desktop computer, and looks at the day's tasks. What planning was finished? What plans are incomplete? What has not even been started yet?

Process Planning Approaches. Thus far, we have considered the kinds of things that a modern CAPP system can do. We also need to look at how it works—the different approaches to how such a system can actually develop a process plan.

One way is to store past process plans and, using a variety of keys, retrieve one that describes a part most like the one that needs to be manufactured. The existing plan may be used as is, or it may be modified to conform to any differences in the new part. This retrieval and modification of existing plans is sometimes called *variant planning.* Its obvious advantage is that the planner does not have to reinvent the wheel. The retrieval can be done by part number, part name, planner name, or any combination of these keys. When using a relational database, other search criteria can easily be included—the machine tools being used, for example.

When a company is making a limited range of products, such as pumps or gears, it may pay to analyze the total database of designs and manufactured parts to determine if parts can be grouped in meaningful families, and then to develop a standard process plan for each family. The analysis takes a substantial amount of staff work, and the approach may not be cost-effective for all limited-range manufacturers. Generally speaking, the more closely related the parts in manufacture are, the more successful the search for parts with similar features is likely to be. For example, a company that makes machines used to assemble doors for different automobile manufacturers might be a candidate. From a layperson's point of view, an automobile door is an automobile door is an automobile door. In fact, however, a maker of auto doors would disagree.

Automobile manufacturers will subcontract the design, development, and delivery of specialized machines that do nothing but assemble doors for a particular product model.

A company known to the author was successful in bidding on several of these contracts. As a result, their machine design and manufacturing was based on making different machines for different car models. However, an extensive analysis revealed that approximately 75 percent of the 12,000 *distinctly different* parts designed every year could be captured in approximately 22 standard families. And each standard family could be manufactured using a standard process plan with some slight variation to accommodate the limited part differences. As a result, the company was able to improve the efficiency of the manufacturing engineering staff by more than 100 percent.

Another approach is to retrieve a somewhat related process plan, copy relevant operations out of it, and paste them into the new plan. A database of available machine tools can be very useful when it includes standard texts for the particular operations that can be performed by each of them. For example, one may have a class of turning machines and a class of milling machines. The individual machines that are available in each class are then listed, each with a set of standard texts that the process planner can use to describe the operation in detail. This kind of approach not only enhances the efficiency of the process planner, it also enhances the clarity of communication with shop floor personnel because the same or similar text is always used to describe operations. It invariably leads to higher quality and less rejects.

If it is not possible to successfully retrieve and use past experience for a particular part, then one has to start from scratch—hopefully without reinventing the wheel.

To make the development of process plans easier, process planning systems should have word processing capabilities with word-wrap and spell checking to help maximize readability. A cut and paste capability is very useful so that at least pieces of text, if not the whole thing, can be retrieved, brought into the new plan, and modified. In start-from-scratch systems, standard text for machine operations can greatly enhance efficiencies.

Special Process Planning System Capabilities. The process planning system should be linked to the in-house computer-aided design systems so that drawings or parts of them can be included in process plans. It is increasingly clear that text, combined with photographs, graphics, video clips or captures, or voice can greatly improve the shop floor worker's understanding of instructions and his or her ability to follow them accurately.

It is also useful to have zoom capabilities so that important details can be cut out of the original drawing and included in the new plan. A simple computer-aided design system in the computer-aided process planning system enables the planner to generate simple process drawings and sketches that will further clarify intent and instructions, especially for operations that are not immediately obvious.

The trend today is away from process plans that are text-heavy to a more pictorial process planning environment where text tells only a small part of the story.

Revision History and Sign-Off. A revision history capability is essential in a modern computer-aided process planning system—complete records of all revisions made to each plan over time must be maintained.

Once a process plan has been completed, it normally goes through a sign-off cycle (peer review) to make sure that the right manufacturing processes are being used to accomplish the design intent. The sign-off process often involves a fixed sequence of checkers, quality control personnel, and others. Each reviewer can approve, reject, and/or make remarks (redlining) on the plan and return it to the original planner for modifications if so required.

After modifications are made, the plan can be used on the shop floor. As it proceeds, further changes may be made for one reason or another. It is essential that they be recorded and tracked.

Links to Other Systems. The most useful of current advanced CAPP systems are capable of linking to other in-house systems. In this context, links to legacy systems are usually most important. In-house manufacturing legacy systems are likely to contain substantial databases of manufacturing experience. Links to financial systems may be used to record when work is done.

The product data management (PDM) system not only functions as a vault for finished drawings, but may also handle configuration control of the final product. Drawings released from engineering to manufacturing engineering for process planning mostly go through the PDM system.

Another important link is to the computer-aided design system. Along with the PDM system, the CAD system provides a base for engineering designs. It is also a source of drawings or parts of drawings to be included in process plans.

A link to the company's enterprise resource planning (ERP) system is vital. In a discrete manufacturing environment, the sale of a product drives the delivery schedule and, in turn, the master production schedule, and then the ERP system. Sometimes the ERP system will do the complete master scheduling. It will release work orders to the shop floor to start certain tasks at certain times.

The input to the ERP system from the manufacturing engineering office is the routing in a process plan, since it contains the descriptions of the different operations to be carried out, including their setup, and piece times. If the process plan, or especially the routing, is not accurate, then the ERP system output will not be accurate either. Accurate communication between CAPP and ERP is thus critical.

Another useful CAPP system link is to the tool inventory and control system. When a process plan is created, the planner has to make sure that the tools needed to do the work on the shop floor will be available.

Time standards are another area of concern. To establish proper setup times and piece times, companies develop in-house time standards or purchase systems from outside vendors to generate them. Since time standards are essential to the control of setup and piece times for each operation, they are key to the reliability of the ERP system.

When the ERP system releases a work order for a particular part, the work instructions (operations) in the process plan will be released to the shop floor control and management system. The release will not only include the work order header and a list of operation descriptions, but will also contain the detailed process plan work instructions. It can be made available in printed form, and—with the proper system—on shop floor terminals as well.

The Spider in the Web. To many observers, a modern CAPP system is the spider at the center of the web of a manufacturing information management system. This is not just the CAPP enthusiast's point of view; it is what one sees when looking at a modern manufacturing data flow diagram.

The design of the product itself and, possibly more important, the design of the manufacturing and assembly processes determine the cost and the quality of a part or an assembly. While business systems and configuration control systems such as PDM and ERP schedule and configure the product, how it is made (i.e., how the design intent is translated in a manufacturing intent) is the crucial factor in determining if a product will be successfully manufactured, i.e., a process plan determines an acceptable and repeatable quality for a reasonably priced product.

A key feature of an advanced computer-aided process planning system is the feedback mechanism that enables people on the manufacturing or shop floor to type in comments about a particular operation or process plan for manufacturing engineering use. Process planning does not compete with product data management or enterprise resource planning, it provides a capability that supports both systems.

The Costs of Tailoring the System. The design of manufacturing and assembly processes reflects the basic business processes of a company. Since they are different for each company, a commercial off-the-shelf (COTS) CAPP system must be configured to individual customer needs in order to work effectively. A fixed CAPP system, with its inherent manufacturing business process definition, does not work because business processes in every company are based on old traditions and can seldom be changed.

The price of implementing an advanced computer-aided process planning system is determined by the costs of tailoring the COTS software. Before embarking on the introduction of an advanced CAPP system, a company first needs to critically analyze its manufacturing business practices. It is likely that irrational habits and practices may have crept in.

There is little doubt that a great deal of money can be saved by analyzing the company's real process planning needs in terms of *needed* business processes. Discontinuing the unneeded business processes would then save a great deal more money.

To really appreciate all that is involved in these issues, it is useful to consider the range of manufacturing information systems, their relationships with each other, and the role played by modern computer-assisted process planning.

A CLOSE LOOK AT MANUFACTURING SYSTEM RELATIONSHIPS

A useful way to look at manufacturing information systems is to consider the work flow in terms of four processes. In this scenario, as illustrated in Fig. 14.2.2, process I deals with engineering and product data management—the definition and configuration of the final product. Process II deals with the definition of the manufacturing and assembly methods used to create the final product. Process III—usually MRP or ERP—deals with logistics, including inventory, scheduling, finance, and order release, all in relation to the product master schedule. Process IV deals with the execution of the manufacturing and assembly of the final product.

As a rule, the software systems for processes I and III tend to have standardized capabilities and are very expensive to buy and implement. A great deal of installation and implementation time and effort is required to link them to systems already being used in the enterprise. As discussed previously, they are somewhat useful in aircraft and aerospace environments, but generally do not provide the highly specific details required for actual aerospace manufacturing.

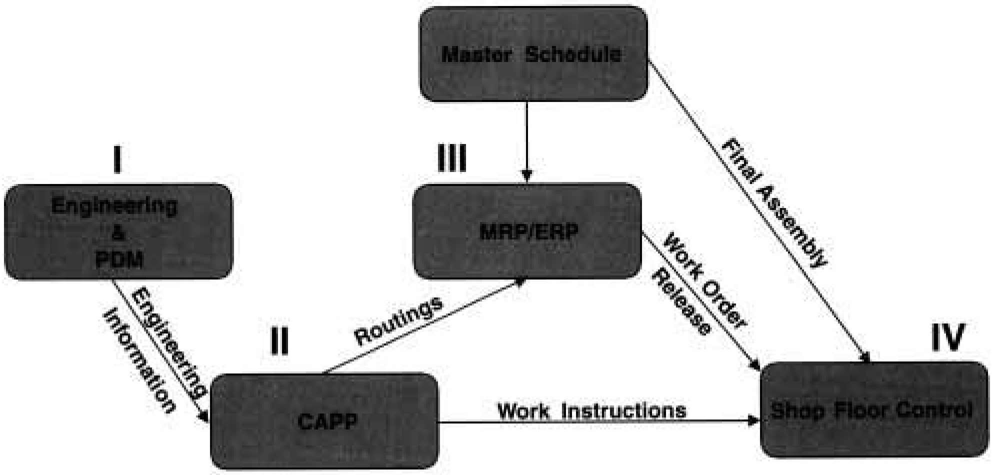


FIGURE 14.2.2 Process relationships.

PROCESS DESIGN AND PLANNING

The Need to Integrate Standardized and Customized Systems

To better understand the roles of information in manufacturing, it is useful to look at process II and IV more closely. Properly implemented, systems that relate to processes II and IV encapsulate the company's manufacturing know-how and experience by incorporating records of its best practices—details of the very specific ways that the company conducts its manufacturing and assembly processes.

When dealing with company-specific manufacturing and assembly methods and execution, very few enterprises are likely to change their detailed practices to fit a standardized software product. They want packages that can be customized to conform to their established ways of doing things.

The most effective solutions can be found in hybrid software systems that combine a core of standardized COTS capabilities with accommodations for types and levels of configuration required to make them responsive to the company's individual need. Such solutions make it possible for the users to take advantage of the economies and efficiencies inherent in standardized packages without sacrificing any of their best engineering or manufacturing practices.

Recognizing User Needs

In the preceding section of this discussion, we focused our attention on operational needs in information technology development, particularly as they apply to complex manufacturing. We must also consider the human needs. Regardless of how much automation there might be in any environment, people make the basic and most critical decisions. If a computerized system is to be truly effective, it must be appropriate to the people who use it.

The persons most intimately involved in manufacturing and assembly are manufacturing engineering staffs, quality procedures and inspection personnel, and all shop floor operators. Their expertise and skills are in manufacturing technology, not in computers. More than 90 percent of their manufacturing information system contacts are with process II and process IV software packages, most notably CAPP and MES systems. Since they are generally manufacturing people and not computer experts, these CAPP and MES packages must be designed for intuitive ease of use, reflecting workers' need of information as their manufacturing tasks progress. In other words, it is imperative that they have user-friendly, highly interactive graphical user interfaces, and that these interfaces are familiar to the users, reflecting the manufacturing and assembly practices that they know.

If at all possible, the interfaces should be the same or similar for both the definition and the execution of manufacturing and assembly methods (processes II and IV), and should complement the functions of engineering and product data management and MRP or ERP systems.

The availability of modern computer technologies on multiple platforms makes these kinds of similar user interfaces possible for all personnel associated with the actual manufacturing work. Systems that take full advantage of these capabilities will greatly facilitate efficiency, quality control, and accountability in the manufacturing and assembly process. And user-friendly, familiar, and consistently structured graphical user interfaces can generate great benefits in terms of efficiency, shorter learning times, and reduced interpretation errors.

PAPERLESS MANUFACTURING, PAPER-SPARSE MANUFACTURING, OR PRINTED INSTRUCTIONS

Although the advantages of electronically available information are very attractive, its use on the shop floor may not always be practical.

On the surface, the current low-cost personal computers (PC) may be justifiable when compared to the costs of scrap and rework caused by poorly understood instructions. In reality, however, it is difficult to visualize that the workers crawling around in the cockpit of an aircraft will be able to consult a PC or even a laptop to review their work instructions. In such environments, a *paper-sparse* approach might be better.

With such an approach, computers are strategically located so that a worker can call up and review a process plan when and where needed. The worker could then select an operation's process plan, quickly print out a copy, and then carry it into the belly of the aircraft or wherever else he or she is working. Paper-sparse may be a more realistic approach for most companies.

However, in some companies established practices are very hard to change, and the price of change may be too high, in terms of money, worker morale, and ultimate production quality. At this end of the spectrum, the plan can be composed electronically, but will still be distributed to the shop floor in familiar printed form.

WHY SHOULD ONE INVEST IN ADVANCED CAPP?

It would be nice if a manufacturing engineer could make a detailed return on investment calculation for the implementation of a modern CAPP system, deliver it to management, and use it to convince them of the need to invest in such a system. However, there is no "cookbook" for making such calculations; the starting point (the current system) and the objective (exactly what is wanted in the long run) will always differ from company to company.

Since many CAPP systems have been installed in the last 10 years, some information about return on investment can be gleaned from experience. Virtually all companies that have implemented such a system, either by developing one themselves or purchasing one from a software vendor, have found it to be very profitable. A common reaction from shop floor personnel, as well as from manufacturing engineering management, is that they cannot imagine where they would be if they had not invested in CAPP. However, profitability analyses have mostly been performed by enthusiastic users, and the results may not be supported by an accountant. Consequently, hard profitability numbers are hard to find.

Based on these last 10 years' experience, process planner efficiency can be improved by a factor of 30 to 100 percent, compared to handwritten planning. Furthermore, companies may be forced to translate design intent into detailed manufacturing instructions if they want to be certified in any of the newer quality control programs such as ISO 9000. If there is no way to make the manufacturing intent clear and check it against final product quality, there is no way that one can be certified for ISO 9000. Not having such a system can thus be very expensive.

The proper documentation and factory transmission of engineering change orders (ECOs) and manufacturing change orders (MCOs) are serious problems in virtually every manufacturing enterprise. If a company uses a handwritten system, then the follow-up on ECOs and MCOs tends to be very haphazard. Furthermore, no documentation is being carried to prove that these changes have been accomplished. Again, the costs of such problems are often hard to pinpoint, but there is no doubt that they can be very significant.

It is also difficult to put a figure on the advantages of consistently using the best experience available in a company with advanced CAPP's retrieval power. It pays off in process planning efficiencies and in lower rejection rates and higher quality.

The combination of standard instruction text, regular freehand text, graphics, photographs, videos, and voice will substantially increase the clarity of instructions sent to the shop floor. Clearer communication results in fewer chances for misunderstanding and production errors.

The hundreds of companies that have introduced advanced CAPP have generally found the return on investment to be between one and three years. The cost basis includes not only

PROCESS DESIGN AND PLANNING

the process planning system software, but also the network and computer hardware needed for effective implementation. With the low cost of PCs today, the return on investment is even more appealing.

Companies sometimes think that introducing a product data management (PDM) system and an enterprise resource planning (ERP) system will solve all their manufacturing problems. That is hardly the case. The value of an ERP system is diminished, for example, without a good process planning system to feed complete and accurate routing information. It is the integration of PDM, process planning, ERP, and shop floor control that provides the foundation for modern manufacturing information management.

THE FUTURE OF CAPP

For many years, a debate has raged about whether variant planning or generative planning (when plans are automatically generated from scratch) will be the process planning technology of the future. Variant planning is based on retrieving existing planning and using it directly or making slight modifications to reflect specific part characteristics. A generative planning system would include every possible combination of features that might be manufactured or assembled, and a set of artificial intelligence rules that could use them to generate a process plan from scratch every time. Ideally, one would have a computer-aided graphics system that would automatically understand the manufacturing features (sometimes different from the design features) and, based on the combination of features, generate the process plan.

Such a solution would be very elegant, but it might not be cost-effective. The artificial intelligence rules have to be set up, and then maintained as manufacturing technology changes over time. While it is theoretically possible to set up such rules and proceed, the reality is that many large aerospace companies have found it to be an effort with limited rewards and seemingly infinite costs.

In discussing this artificial intelligence (AI) concern with several large aerospace and defense firms, it appears that it is possible to set up artificial intelligence rules based on features of families of relatively simple parts, such as sheet metal parts, gears, and shafts, and to generate process plans automatically. And process planning for some assembly activities, such as checking and some riveting can be done using AI rules. Setting up and properly implementing rules for complex parts and assemblies is another matter. We are a long way from being able to build aircraft with generative process planning. For the foreseeable future, we can expect to see more combinations of variant and generative planning.

On another front, there has been much talk about paperless manufacturing. Paperless is not always best and paper-sparse is sometimes better. As in the variant versus generative argument, pragmatism is the watchword. Sometimes a combination of electronic and paper may be the best way to go.

Given the speed demanded to get products on the market in today's global economy, the length of the product design and manufacturing cycle must be as short as possible, with maximum efficiency, low cost, and high quality. The definition of manufacturing processes, based on the design intent, is the most crucial part of that cycle. It can determine manufacturing costs, delivery time, and quality.

It is therefore likely that CAPP applications will increasingly go beyond electronic pencil–driven systems to fully integrated systems. In the battle between expensive integrated systems and lower cost error-prone manual systems, practical realities must be considered. The implementation of specific approaches may not depend only on their economics. Local traditions and business practices, as well as the costs of capital and salaries, will play important roles in the future of process design and planning.

BIOGRAPHY

Alexander Houtzeel, founder and president of HMS Software Inc., was born and raised in the Netherlands. He received his graduate degree in manufacturing from the Delft Institute of Technology and his graduate degree in nuclear engineering from the National Institute of Nuclear Science in Saclay, France. He was employed in the nuclear engineering field in the United States and France for 12 years. Since 1972, Houtzeel has been heavily involved in computer-aided manufacturing in the United States and has pioneered in the fields of computer-aided group technology and process planning. He has written numerous papers on CAD/CAM.

CHAPTER 14.3

MANUFACTURING PROCESS DESIGN USING STATISTICAL PROCESS ANALYSIS

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This chapter describes the statistical modeling of manufacturing and service processes based on a specification of customer requirements using nominal values and tolerance limits for all parameters of a product. Also described are the improvement and control of the process, so that the requirements will be satisfied, together with proof of the conformance to these requirements. The aggregate of several different multivariate statistical procedures for the modeling according to the cause-and-effect principle is called statistical process analysis (SPA). The input and process parameters are the causes, which impact the product parameters as the effects of the process. Further aspects of SPA include the structuring of a company as a network of manufacturing and service processes and the improvement of the communication between the processes. The change from a hierarchical into a process-oriented organizational structure, which will improve both quality and financial indexes such as productivity and costs will also be discussed.

BACKGROUND AND SITUATION ANALYSIS

Quality Indexes

Everybody speaks about the quality of products and services, but very rarely do you meet someone who can explain what it is and how it can be measured. This is at least the impression you get when reading reports about quality and its development in a company. Philip B. Crosby see [1], for instance, defines quality as the conformance to customer (external and/or internal) requirements, but does not offer a workable method to measure quality. When a product is characterized by one product parameter *Y*, the quality can be measured by the process capability indexes C_p (indicates the relationship between the product specification and the distribution of the product parameters) and C_{pk} (indicates the degree to which the nominal value and the mean of the distribution coincide) (see Appendix, and Refs. [1] and [2]). The capability is the inherent potential of a process to produce goods or services—products—that meet specific requirements. The ability to meet these requirements must be demonstrated by measured performance. The process capability index reflects the relationship between the product's specification, expressed by the nominal value and tolerance limits, and the capability of the process, expressed by the width of the frequency histogram of the observations of one product parameter.

As a rule, a product is characterized by more than one product parameter, which are nonindependent. Therefore, it is necessary to generalize the definition of quality in these cases and to define a new measurement for generalized quality. This new measurement was developed and is called *product capability* [2]. The formulas for the product capability indexes are contained in the appendix. Generalized quality improvement involves three topics: (1) specification of customer (external or internal) requirements, by the nominal values and tolerance limits, for all product parameters, (2) control of the process, so that all requirements are satisfied, and (3) proof of conformance to the requirements.

Financial Indexes

There are different financial indexes, which characterize productivity, profitability, financial viability, effectiveness, and so forth of a company. These indexes have in common a comparison of expenditures and benefits. They are also functions of many other quantities, for instance costs, capability indexes, consumption of material, labor, machines, effectiveness of methods, and know-how of workers and management. The company's ability to survive may depend on its success in the international market and preparation of the overall control mechanisms, which require an increase in financial indexes, for example, the reduction of costs and the improvement of quality.

Organizational Structure

The majority of companies have a hierarchical organization structure. This structure is often too inflexible to generate solutions to common problems. Each company has to be regarded as a network of manufacturing and/or service processes, which means that the result of a process can be either a product or a service. The processes in a network are connected in such a way that the products of previous processes are inputs to the subsequent processes. This is the basis for the *communication* between processes. The owner of a subsequent, or customer, process formulates the requirements for products of the previous processes. The owner of a previous or supplier process specifies all requirements and controls his or her process so that the requirements of the customer are satisfied. Besides this, the supplier has to prove that the products produced in his or her process meet all requirements. Taking into consideration other objectives, such as training of the workers and assistance in the application of a total quality management (TQM) system, a process-oriented organizational structure with the objectives previously specified will be the outcome.

The network of processes and a process-oriented organization structure are the foundation for the improvement of financial indexes, processes and products, reduction of costs, as well as product and process development times.

Definition and Scope of Process Design

Process design can be defined as

Structuring of a company in a network of manufacturing and service processes

Determination of the dependence structure between all input, process, and product parameters

Establishment of communications between the processes of the network by the language with the elements:

- Specification of customer (external and/or internal) requirements
- Proof of conformance to the requirements
- Control of the processes so that the requirements are satisfied

Change from the hierarchical-oriented to a process-oriented organizational structure in which the main objectives of specification, control, and proof are given the highest priority

STATISTICAL PROCESS ANALYSIS (SPA)

What Is SPA?—Methodology

SPA is an aggregate of the most important multivariate statistical procedures, which can be successfully applied in an industrial situation.

The specification of customer requirements, expressed by the nominal value and tolerance limits for all product parameters, which characterize the product, has to be established using general knowledge of the product and the product equation. It should be noted that the product equation, in which one product parameter is expressed as a function of the rest of the product parameters, has to be solved on the basis of observations of all product parameters using multivariate statistical procedures—for instance, regression analysis, see Ref. [3].

The product parameters are nonindependent as a rule. Therefore, it is not sufficient to prove conformance to the requirements, while simultaneously using the process capability analysis for each product parameter. A generalization is necessary. The multivariate generalization of the process capability indexes in relation to the product capability indexes is made (see Ref. [2]), and the appendix for a list of the most important formulas. Each process of the network has to be controlled using a process equation. This equation is solved using regression analysis.

It is necessary to emphasize that the cause-effect principle is applicable to the processes, in which the input and process parameters are the causes, which impact the product parameters as the effects. A change of the product parameters can be achieved only by changing the input and process parameters.

In a network of processes, the input parameters of any process are the product parameters of the products of previous processes. It is also important to note that the nominal values of the product parameters are the target values of the control procedure. Table 14.3.1 simplifies the application in a brief outline.

Why Use SPA?—Benefits

SPA is necessary in cases in which the financial indexes, such as productivity and costs, are unsatisfactory, the quality of products is poor, or the communication between processes is inadequate. Decision criteria for using SPA are provided by the capability analysis. As shown

TABLE 14.3.1 Brief Outline of SPA Procedures

Subject of research	Purpose	Method/procedure
Visual representation of a process or a network of processes	Visual representation of the sequence of working steps or processes carried out by an individual or organization.	Flow diagram
Investigation of the possible causes of a problem	Visual representation of the factors that contribute to the effects.	Cause-effect diagram
Bar charts with respect to the most significant aspects of a problem	Displaying data about a problem, which enables its most significant aspects. Grouped data are displayed in descending order of bar size, beginning with the greatest first. It can be actual values, be expressed as a percentage, or data can be converted into costs.	Pareto analysis
Data collection	Relating data files for input, process, and product parameters.	• Design of experiments including the methods by Taguchi and Shainin • Measurements in the running processes
Graphical representations of data files	• Distribution.	• Histogram, box plots • Box whisker plots
	• Visual comparison of multivariate data sets.	• Star plots
	• Visual representation of dependence between parameters.	• Correlation diagram • Draftsman plots
	• Representation of time dependence.	• Time series plot
Classification of data files	Testing to homogeneity and classifying in integrated groups.	• Discriminant analysis • Cluster analysis
Dependence structure	Dependence between input, process, and product parameters.	• Correlation analysis • Factor analysis
Product equation	Specification of all requirements by calculation of nominal values and tolerance limits for all product parameters.	Regression analysis with stochastic input and process parameters, and selection of optimal subsets of parameters
Process equation	Controlling the process.	
Capability analysis	Proofing the conformance to all customer (internal or external) requirements.	Process and/or product capability indexes
Quality control	Controlling and regulating processes.	Control charts (univariate and multivariate)
Quantify customer requirements	Quantifying subjective information.	Conjoint analysis
Product and process development	Development of new products and processes, further developments.	• Quality function deployment • Product and process equations

in the appendix, if the process or product capability index is smaller than 1, then the values of the product parameters lie outside the tolerance region, which means that the process produces defective products, or the process is out of control. In these cases SPA has to be applied. As a result of a process improvement and the improvement of communication between the processes and the transition from a hierarchical to a process-oriented organization structure, an increase in productivity of 30 to 50 percent is not unusual. The active involvement of workers and management in the problem-solving process is an important factor.

How to Apply SPA?—Procedures

The typical method for handling practical situations is to first split the SPA into two parts:

1. As the *product* evaluation and definition of the problem on the basis of the process and/or the product capability indexes,
2. As the *process* evaluation with improvements and control, including the structuring of the manufacturing and service processes as a network of processes, and the development of a common language for communications between processes, including element specification, as well as control and proof of the conformance

Example of a Typical Situation—Problem Description

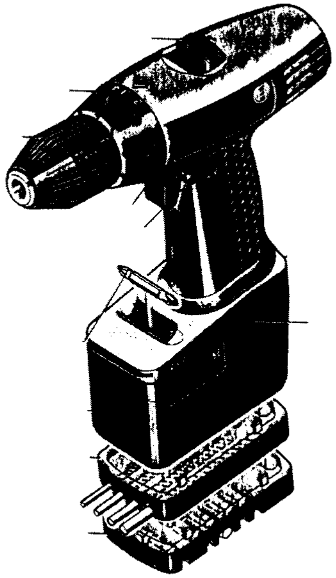

FIGURE 14.3.1 Screwdriver.

To demonstrate the application of an SPA we will use a battery-operated screwdriver (see Fig. 14.3.1) requiring assembly as an example.

It has been determined that the assembly time is too long. The possible reasons could be an unsatisfactory assembly process or low-quality parts for the assembly. To discover the real reason for the problem, a MOST® analysis [4] was completed, using the following assembly parts:

- Two plastic case components
- One motor with keyless chuck and torque-setting ring
- On/off switch with speed control and speed selector
- One bolt
- Carrying loop with adjusting slide
- Screws
- One metal bow
- Miscellaneous parts

The most important result of the MOST analysis is contained in Table 14.3.2.

There is a big difference between the best and worst assembly method, measured in time measurement units (TMUs). This suggests that the quality of the plastic case components is poor. Before an SPA can be started, an exact problem definition must first be completed to avoid a high cost for the SPA. The most concise and precise definition of the problem is given by the *process* capability indexes if there is only one product parameter, or by the *product* capability indexes if there are more than one, nonindependent product parameters. For the calculation of the capability indexes, data for the product parameters is needed. On the basis of the capability indexes, a decision will be made about process improvements. The purpose is to achieve either a reduction in the variability of the product

TABLE 14.3.2 MOST® Analysis

No	Activity	Sequence analysis	Freq.	TMU best	TMU worst
1	Place the 1st plastic case component in the survey	$A_1\ B_0\ G_1\ A_1\ B_0\ P_{3\,(P6)}\ A_0$		60	90
2	Put the motor in the plastic case component	$A_1\ B_0\ G_3\ A_1\ B_0\ P_{3\,(P6)}\ A_0$		80	110
3	Put the switch in the plastic case component	$A_1\ B_0\ G_1\ A_1\ B_0\ P_{1\,(P6)}\ A_0$		40	90
4	Assemble bolt and a reinforcement in the plastic case component	$A_1\ B_0\ G_3\ A_1\ B_0\ P_{1\,(P6)}\ A_0$	(2)	70	170
5	Pin up the carrying loop with adjusting slide	$A_1\ B_0\ G_1\ A_1\ B_0\ P_{1\,(P1)}\ A_0$		40	40
6	Assemble torque setting ring speed selector, and speed control	$A_1\ B_0\ G_3\ A_1\ B_0\ (P_3)_{(P6)}\ A_0$	(2)	110	170
7	Place the 2nd plastic case component on the 1st	$A_1\ B_0\ G_1\ A_1\ B_0\ P_{3\,(P6)}\ A_0$		60	90
8.1	Put in the screws	$A_1\ B_0\ G_1\ A_1\ B_0\ P_{1\,(P3)}\ A_0$	(4)	160	240
8.2	Tighten the screws	$A_1\ B_0\ G_1\ (A_1\ B_0\ P_3(F_{16(24)}))A_1\ B_0\ P_1 A_1$	(4)	850	1170
9	Fix the metal bow	$A_1\ B_0\ G_3\ A_1\ B_0\ P_3\ A_0$		80	80
10	Take away the assembled tool and put in the means of transport	$A_1\ B_0\ G_{1\,(G3)}\ A_1\ B_0\ P_1\ A_0$		40	60
		Total:		1590	2210

parameters or an adjustment of the process so that the differences between the nominal values and the arithmetic means become minimal, or control of the process using multivariate control charts. The decision has to be made according to Fig. 14.3.2.

Data Collection

The plastic case components are characterized by four product parameters. These are

Y_1 = thermoshrinkage in percent
Y_2 = deviation from axial measure in mm
Y_3 = deviation from parallelism in mm
Y_4 = thickness of the components at specified points in mm

For these product parameters, $N = 113$ vectors of data are collected from the running process. Another possibility for data collection is the use of the *design of experiments* method, see Refs. [5] or [6].

Graphical Representation of the Data

As a first impression of the data, graphical representations are useful.

Star Plots. The star plot is a graph of multivariate data of the product parameters that enables you to visually compare different observations. Each star consists of a series of rays drawn from a center point, where each ray represents the observed relative value of one product parameter (see Fig. 14.3.3). The star in Fig. 14.3.3 is the key for the stars in the star plots in

MANUFACTURING PROCESS DESIGN USING STATISTICAL PROCESS ANALYSIS

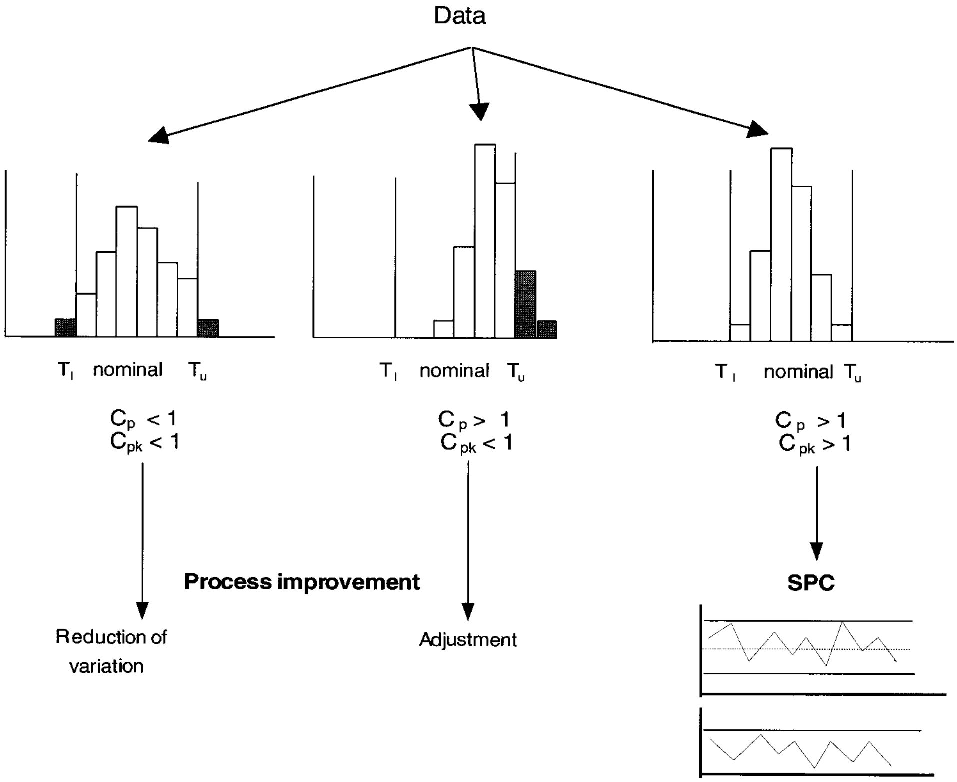
Data
T$_l$ nominal T$_u$
$C_p < 1$
$C_{pk} < 1$
T$_l$ nominal T$_u$
$C_p > 1$
$C_{pk} < 1$
T$_l$ nominal T$_u$
$C_p > 1$
$C_{pk} > 1$
Process improvement
SPC
Reduction of variation
Adjustment

FIGURE 14.3.2 Decision making on the basis of capabilities.

Fig. 14.3.4. The first star in the lower left-hand corner in Fig. 14.3.4 represents the observations of the first product. The last three stars (see top of the right-hand side in Fig. 14.3.4) represent the star plot for (1) the lower tolerance limits, (2) the nominal values, and (3) the upper tolerance limits. The difference between the stars shows that the products are not identical, which suggests that the process has to be improved for the products to be-come more consistent.

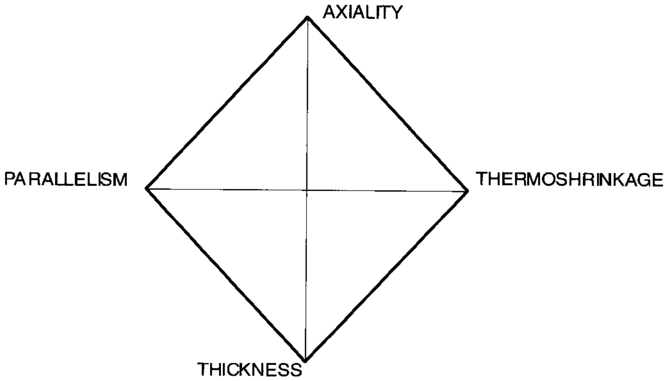
AXIALITY
PARALLELISM
THERMOSHRINKAGE
THICKNESS

FIGURE 14.3.3 Key for the star plots.

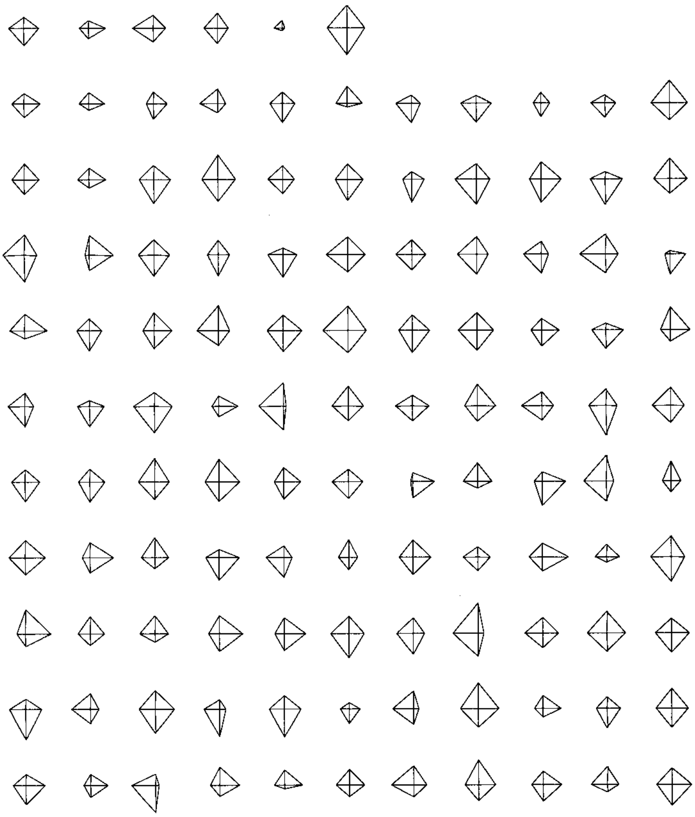

FIGURE 14.3.4 Star plots of the data for the four product parameters.

Correlation Diagrams. For a simple examination of the linear relationship between all pairs of the four product parameters, we plot the correlation diagrams between the six pairs of comparisons of the four product parameters and represent these in Fig. 14.3.5.

Figure 14.3.5 shows that there are linear relationships between the product parameters. By use of a correlation analysis, the degree of these linear relationships between the product parameters can be quantified, where the correlation coefficient is a dimensionless quantity, which satisfies the following properties:

- If all points (Y_{1i}, Y_{2i}) of the scatter diagram lie on a line, then $r_{12} = 1$ or $r_{12} = -1$. The sign of the correlation coefficient depends on the direction of the straight line and the angle of inclination.
- If no linear relationship exists between the Y_1's and Y_2's, then $r_{12} = 0$.
- Generally the correlation coefficients lay in the interval $[-1 < r_{12} < 1]$.

The correlation coefficients are collected in the following correlation matrix:

$$\mathbf{R_{YY}} = \begin{pmatrix} 1 & 0.089 & -0.474 & -0.219 \\ & 1 & 0.439 & 0.214 \\ & & 1 & 0.524 \\ & & & 1 \end{pmatrix}$$

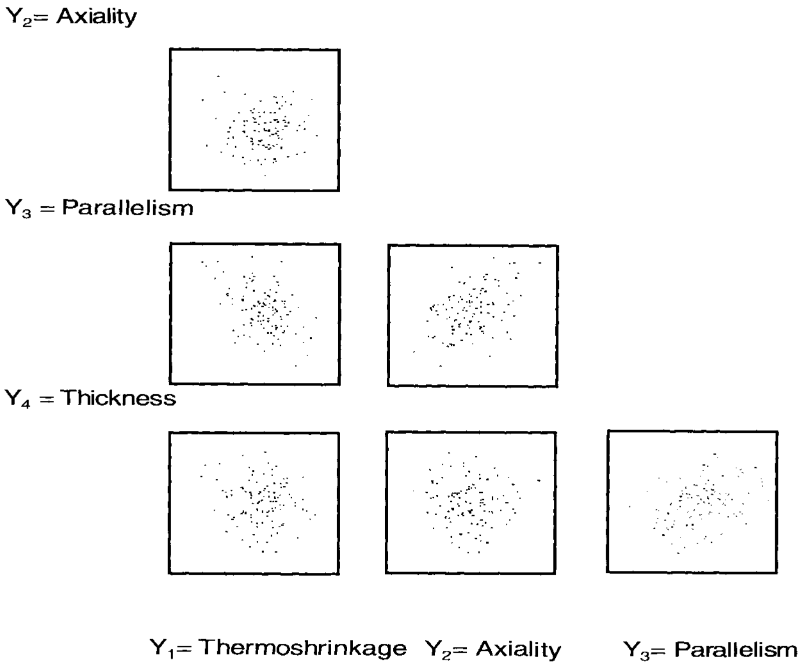

FIGURE 14.3.5 Correlation diagrams for the four product parameters.

We find the largest correlation coefficient $r_{34} = 0.524$ between Y_3 and Y_4, the deviation from parallelism and the thickness of the components at specified points. The conclusion is that the product parameters are not independent.

Histograms. A representative histogram of the product parameters is the thermoshrinkage histogram in Fig. 14.3.6. The figure shows that the histogram can be approximated by a normal distribution. In Fig. 14.3.7 a three-dimensional histogram represents the correlation between parallelism and thickness. From this figure you can see very clearly that the data of the pairs (Y_3 = parallelism, Y_4 = thickness) lies inside an ellipse. The (Y_3, Y_4) plane with these pairs shows the correlation diagram for these two product parameters, represented in Fig. 14.3.5. For three of the four product parameters the nominal value and tolerance limits are specified in Table 14.3.3. For Y_4 the nominal value and tolerance limits have to be calculated.

Calculation of the Nominal Value and Tolerance Limits

In most cases the nominal values and tolerance limits are calculated by using theoretical relationships between the product parameters; however, when these relationships are unknown, it becomes beneficial to use multivariate statistical procedures for the calculation. It is important to note that the final step, when specifying product and process design, is to determine tolerances around the nominal settings identified by the parameter design. Likewise, it is still common practice within industries to assign tolerances by convention rather than scientifically.

Because tolerances that are too narrow will increase the manufacturing cost, whereas tolerances that are too wide will increase performance variation, it is necessary to calculate the nominal value and tolerance limits for all product parameters.

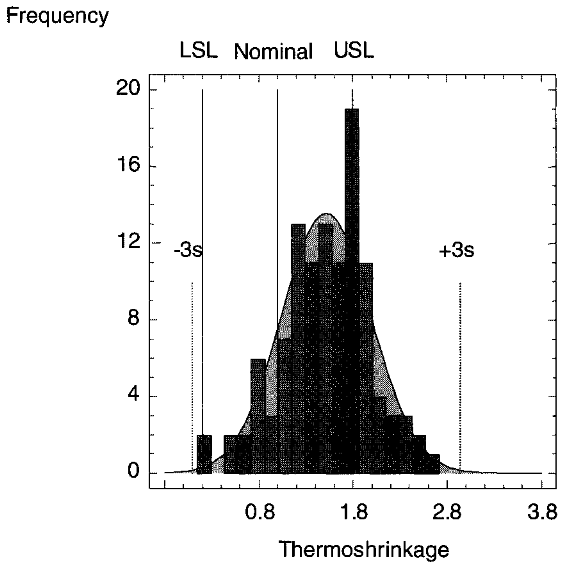

FIGURE 14.3.6 Frequency histogram for thermoshrinkage.

In the present case, the multivariate regression analysis, will be used to compute the *product equation* [7]. The product parameter, for which the nominal value and tolerance limits are needed, is represented as a linear combination of the rest of the product parameters. The product equation for Y_4, dependent on the remaining product parameters, is

$$\hat{Y}_4 = 3.049 + 0.04479\ Y_1 - 0.04575\ Y_2 + 0.10135\ Y_3$$

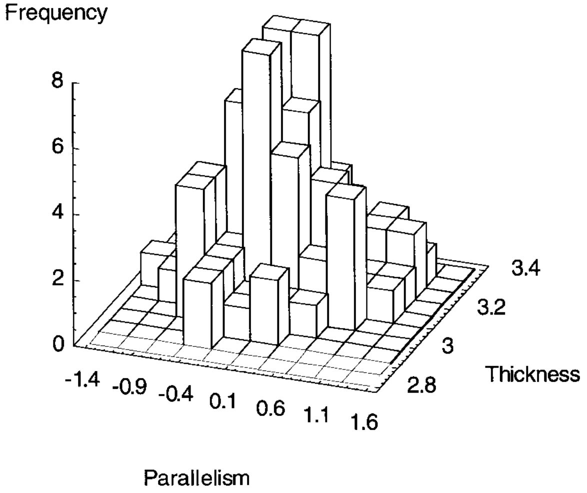

FIGURE 14.3.7 Three-dimensional histogram.

TABLE 14.3.3 Nominal Values and Tolerance Limits for the Product Parameters Y_1, Y_2, and Y_3

Product parameter	Description	Nominal values and tolerance limits
Y_1	Thermoshrinkage	$[0.2 \le Y_1 \le 2.0]$ (%)
Y_2	Deviation from axial measures	$[-0.3 \le Y_2 \le 0.3]$ (mm)
Y_3	Deviation from parallelism	$[-0.6 \le Y_3 \le 0.6]$ (mm)
Y_4	Thickness of the plastic case components in specified locations	Not specified

The standard deviation of the residuals $\hat{Y}_4 - Y_4$ is $S_{Y/1,2,3} = 0.084$, where the product parameters are denoted by their indexes.

When placing the nominal values of Y_1, Y_2, and Y_3 in the product equation for Y_4, the nominal value of Y_4 is $M_4 = 3.098 \cong 3.1$. Likewise, when placing the upper and lower tolerance limits (T_l and T_u) for Y_1, Y_2, and Y_3 into the product equation of Y_4, the tolerance limits for Y_4 are $T_{1.4} = 2.9$ and $T_{u.4} = 3.3$.

Using the relation

$$T_l T_u = no\ \min al \pm \sqrt{\chi^2_{m,1-\alpha} \cdot S^2_{j/m-j}}$$

where m is the number of product parameters, $S^2_{j/m-j}$ is the conditional sample variance of the jth product parameter in dependence of the rest of product parameters, and $\chi^2_{m,1-\alpha}$ is the $1 - \alpha$ percentile of the chi-squared distribution, the statistical tolerance limits can be calculated as well.

Decision Making on the Basis of Capability Indexes

The capability index indicates the relationship between the product's specification (planned tolerances) and the distribution spread (natural tolerances) of the values of the product parameters.

Several factors influence the increase or decrease of the capability indexes. These include the initial process and product design, which—in most cases—are consistently capable of affecting the requirements or the common causes encountered during the operations (i.e., variation in environmental variables, product deterioration, and manufacturing imperfections).

After the calculation, the nominal values and tolerance limits for all product parameters are known. The process and product capability indexes can now be calculated. First, consider the calculation of the process capability indexes C_p and C_{pk}. The following formulas are used for the calculation

$$C_p = \frac{\text{specification spread}}{\text{spread of histogram}} = \frac{T_u - T_l}{6 \cdot s_Y}$$

where s_Y equals the standard deviation of Y.

The corrected process capability C_{pk} then indicates the degree to which the nominal value of the product parameter and the mean value of the process coincide. C_{pk} is calculated as follows:

$$C_{pk} = (1 - k) \cdot C_p$$

where

$$k = \frac{\text{process shift}}{\text{half of process specification}} = \frac{|\text{mean} - \text{nominal}|}{\text{half of process specification}} = \frac{|\overline{Y} - M_Y|}{\frac{1}{2}(T_u - T_l)}$$

and M_Y is the nominal value.

TABLE 14.3.4 Process Capability Indexes

	Y_1	Y_2	Y_3	Y_4
C_p	0.63	0.48	0.40	0.71
K	0.46	0.032	0.13	0.18
C_{pk}	0.34	0.47	0.35	0.58

The calculation of these indexes for the product parameters Y_1 to Y_4, independent of each other, gives us the values in Table 14.3.4. The process capability analysis shows that the distributions (histograms) of the four product parameters Y_1, to Y_4 are larger than the widths of the tolerance intervals, because the C_{pk} values are smaller than 1. From this follows that the process produces products with product parameter values that lie outside the tolerance limits. The process is therefore out of control, because it produces defective products. This causes the large difference between the best and worst case (TMUs). The process has to be improved so that the values of the product parameters will appear inside the tolerance intervals.

By calculating separate process indexes for each individual product parameter, the correlation between the product parameters is ignored, which is a definite weakness. To illustrate the benefit of a multivariate approach, a product described by two product parameters should be considered. It is assumed that both quality characteristics have bivariate normal density. Furthermore, we assume a positive correlation coefficient ρ_{12} between the two product parameters.

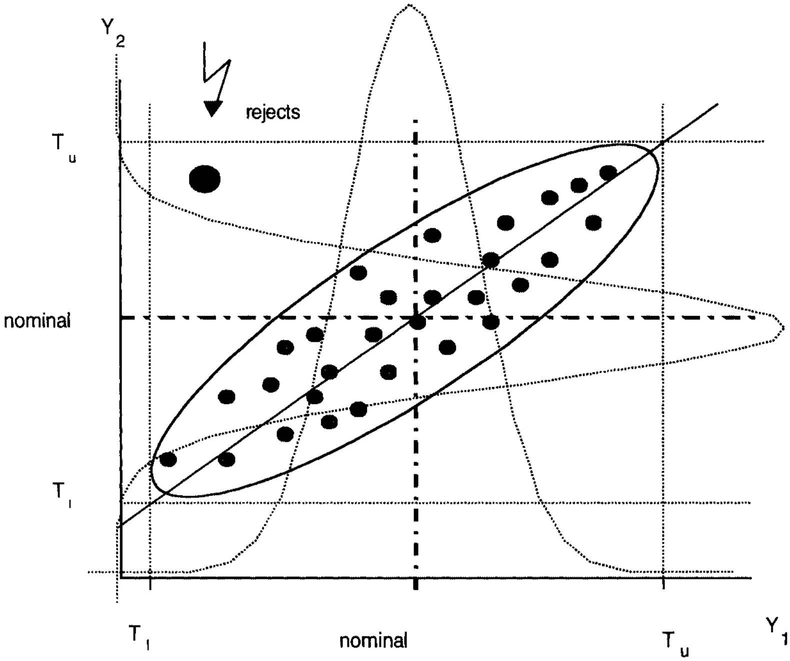

FIGURE 14.3.8 Elliptical region of distribution and rectangular region of tolerances.

If both samples range within their respective tolerance limits, then the process seems to be in statistical control. But is it really so? The use of separate calculations is equivalent to the plots of Y_1 and Y_2 on a single representation in Fig. 14.3.8, which superimposes one Y representation over the other.

One must, however, remember that using separate representations of the rectangular domain, can be very misleading, especially since the "true" control domain in regard to the normal distribution of both product parameters is elliptical in its natural state. Hence, the process is out of statistical control if some values of both product parameters lie outside the elliptical domain.

The size of the correlation coefficient between the two product parameters affects the size of the elliptical domain. If, for example, both product parameters are distributed independently of each other, then the control domain is a circle, thus making the rectangular domain incorrect. If the correlation coefficient is nearly 1, then the elliptical domain approaches the "cigar" form. But both forms are very different from the rectangular domain. If the quality is assessed using the rectangular domain, then the quality is incorrectly estimated.

The mistake of assuming a rectangular domain manifests itself in the process capability indexes, which are too high. It could occur that the company makes a decision against a necessary process improvement, on the basis of incorrect process capability indexes. This means that the company would sell a product of bad quality without noticing this fact. The customer will be misled. A correction is necessary and can be done, see Ref. [2]. The corrected process capability indexes are smaller than before the correction.

Another correction of the process capability indexes is the multivariate generalization of the product capability indexes, which are represented in the appendix. The formulas in the appendix produce the following results: $PC_p = 0.126$, $K = 0.42$ and $PC_{pk} = 0.77$. Using the decision rule in the univariate case, it is obvious that the process producing the plastic case components has to be improved so that the variations of the product parameters will be reduced and the relationship between the nominal values and the arithmetic means is improved.

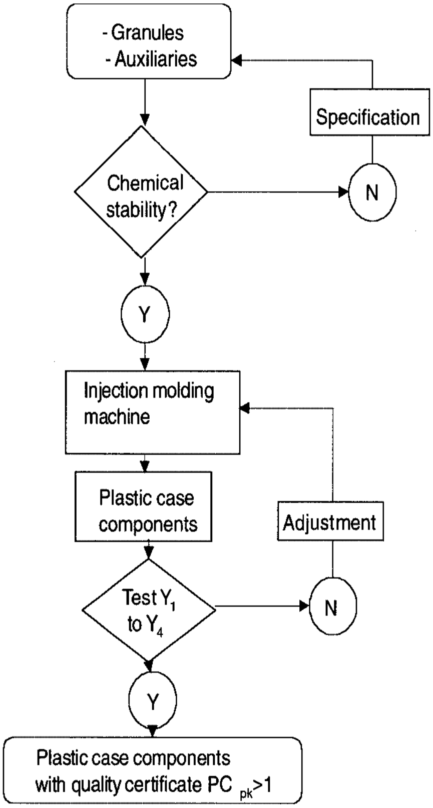

FIGURE 14.3.9 Flowchart of the plastic manufacturing process.

Process Improvement

After the statistical evaluation and analysis of the product and the calculation of the process and product capability indexes, the problem in the manufacturing of the plastic case components can be defined simply as $PC_{pk} < 1$.

Brainstorming, Flowchart, Cause-Effect Diagram. Brainstorming with the workers in the plastic manufacturing process, yielded the flowchart of the activities as shown in Fig. 14.3.9 and the cause-effect diagram in Fig. 14.3.10 as a graphical representation of the cause research.

Network of Processes. As seen in the assembly process of the screwdriver, the plastic case components are inputs in the assembly process and at the same time products of the plastic manufacturing process. The initial problem with large differences in the time standards (TMUs) for the best and worst cases can be solved by improving the communications between these processes. In this case, the assembly process specifies its requirements to the plastic manufacturing process by computing the nominal values and tolerance limits for all product parameters of the plastic case components. This is done by calculating the nominal values and tolerance limits for the four product parameters Y_1 to Y_4. Now the plastic manufacturing process has to be controlled with the nominal values as targets so that the plastic case

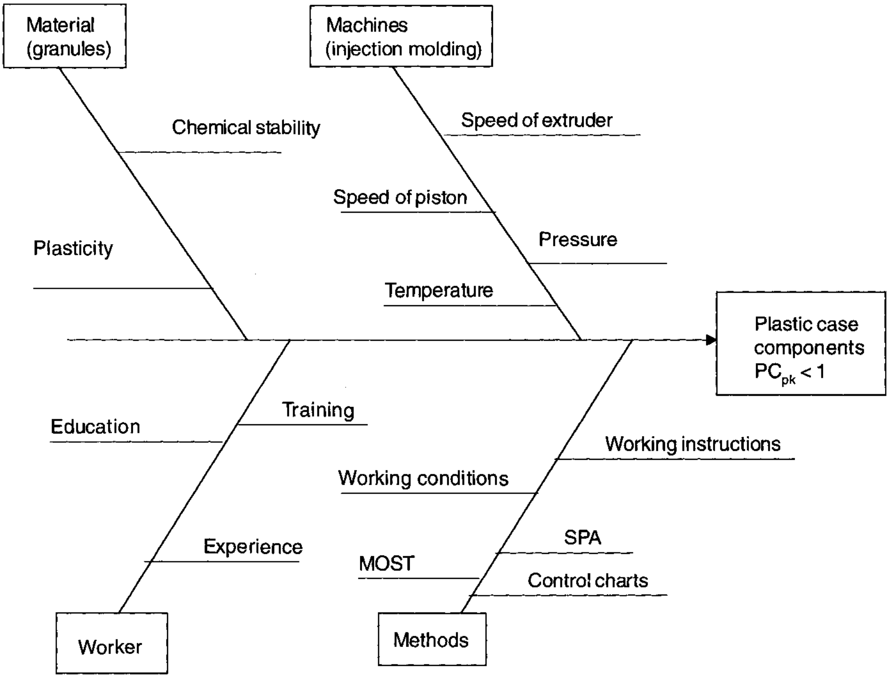
Material (granules)
Machines (injection molding)
Chemical stability
Speed of extruder
Speed of piston
Plasticity
Pressure
Temperature
Plastic case components $PC_{pk} < 1$
Training
Education
Working instructions
Working conditions
Experience
SPA
MOST
Control charts
Worker
Methods

FIGURE 14.3.10 Cause-effect diagram of the problem $PC_{pk} < 1$ in the plastic manufacturing process.

components will satisfy the specified requirements. The owner of the process has to prove that the plastic case components satisfy all requirements. An illustration of the structure of this network is provided in Fig. 14.3.11.

Process I in this figure could be the plastic manufacturing process, process II could be the process producing other parts of the screwdriver, and process III, the assembly process. The owner of the assembly process specifies the requirements for the plastic manufacturing process and for the other process by calculating the nominal values and tolerance limits for product parameters of these processes. The owners of the previous processes will control their processes so that all requirements are satisfied and prove that the requirements are satisfied for the finished products.

Process Equation. For control of the plastic manufacturing process, shown in Fig. 14.3.12, data is needed for the input, process, and product parameters. The product parameters are unchanged. The process parameters are

X_1 = relative speed of the extruder and the piston percent
X_2 = temperature of the injection molding °C
X_3 = mvi (mass volume index)
X_4 = density of the material
X_5 = mass temperature °C

The process parameters are not independent of each other. The dependence structure is specified in the correlation matrix in Table 14.3.5. The process parameters are very highly correlated; for instance, the process parameters X_5 (mass temperature) and X_3 (mass volume index), or X_3 and X_4 (density of the material).

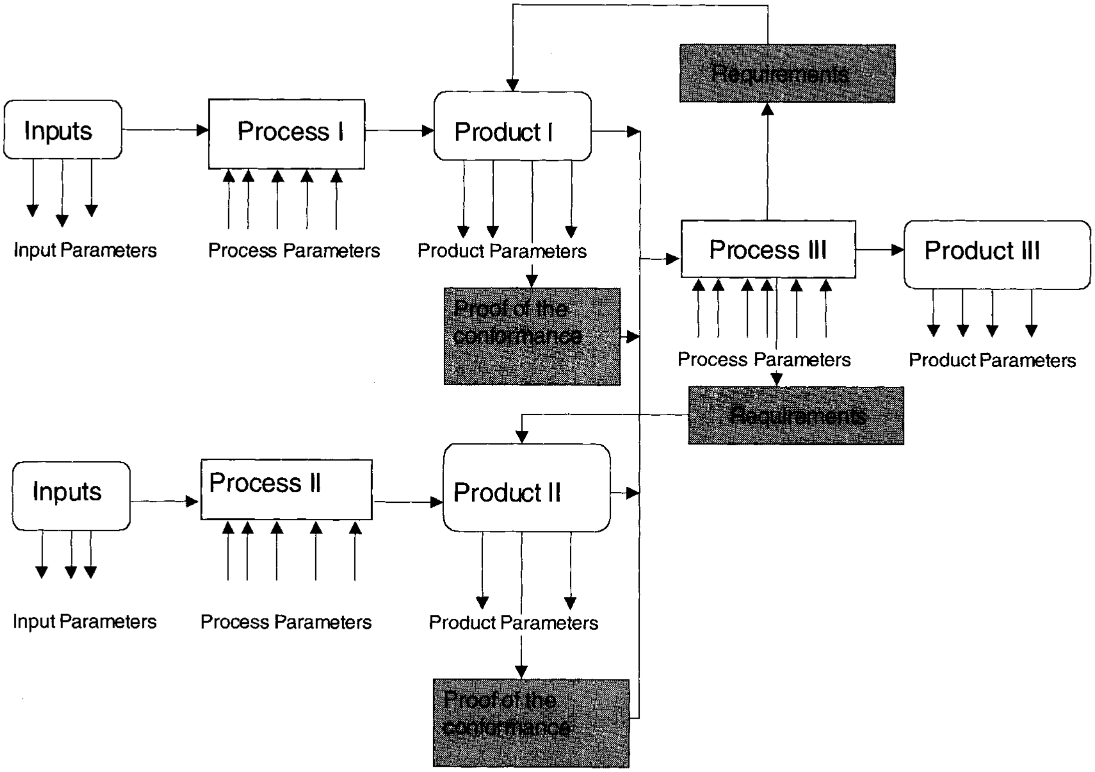
Requirements
Inputs
Process I
Product I
Input Parameters
Process Parameters
Product Parameters
Proof of the conformance
Process III
Product III
Process Parameters
Product Parameters
Requirements
Inputs
Process II
Product II
Input Parameters
Process Parameters
Product Parameters
Proof of the conformance

FIGURE 14.3.11 Network of processes with communication.

Because the process parameters are not independent of each other, it is impossible to conclude which process parameter has to be changed to attain a desirable change of the plastic values for the case component. If X_1 is changed, the effect will cause changes of Y_1 and Y_2, as well as of X_2 to X_5. Because X_2 to X_5 are influenced by the change of X_1, these changes influence Y_1 and Y_2 as well, as can be seen in Fig. 14.3.13.

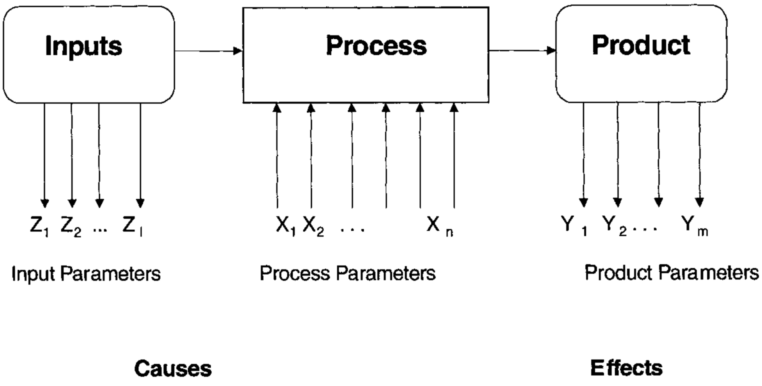
Inputs
Process
Product
Z1 Z2 ... Zl
X1 X2 ... Xn
Y1 Y2 ... Ym
Input Parameters
Process Parameters
Product Parameters
Causes
Effects

FIGURE 14.3.12 Process representation.

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TABLE 14.3.5 Correlation Matrix for the Product Parameter Y_1 and the Process Parameters

	Y_1	X_1	X_2	X_3	X_4	X_5	
	1	−0.136	0.414	0.276	−0.410	0.223	Y_1
		1	0.561	0.346	−0.107	0.319	X_1
R =			1	0.447	−0.371	0.547	X_2
				1	−0.878	0.838	X_3
					1	−0.782	X_4
						1	X_5

In addition, the changes can be positive or negative. Therefore, we have a situation where the process and product parameters are mutually dependent in a very complicated relationship structure. Nobody can disentangle this chaos if all process parameters are changed. From this follows that we need an instrument to unravel the chaos. This instrument will also give us multivariate statistics. This instrument is the *process equation* considering one or more product parameters and the input and process parameters.

The process equation for Y_1 (thermoshrinkage), which is dependent on the five process parameters, looks like this:

$$Y_1 = 27.902 - 0.389\, X_1 + 0.0679\, X_2 + 0.0089\, X_3 - 8.653\, X_4 - 0.193\, X_5$$

How can we use this process equation?

To control the process using the process equation, the values of the product parameters of the finished products must fall within the tolerance interval $[0.2 < Y_1 < 2.0]$.

To make this statement more precise, we need the mean squared error of the prediction, which can be calculated using the formula

$$U_{N,n} = \sigma^2_{Y/X} \cdot \left(1 + \frac{n}{N - n - 1}\right) \text{ and } \sqrt{U_{N,n}}$$

This calculation requires the standard deviation $s_{Y/X}$ for all observations of Y_1, related to the process equation, resulting in a value of $s_{Y/X} = 0.35$. By using the square of the standard deviation called *variance* for the observations of Y_1 related to the process equation, a very important measure in determining the process through the input and process parameters can be calculated. This measure $R^2_{Y/X} = 0.45$, which means that 45 percent of the variance of Y_1 will be a function of the input and process parameters. The measure has a low value, because we have only considered a subset of input and process parameters.

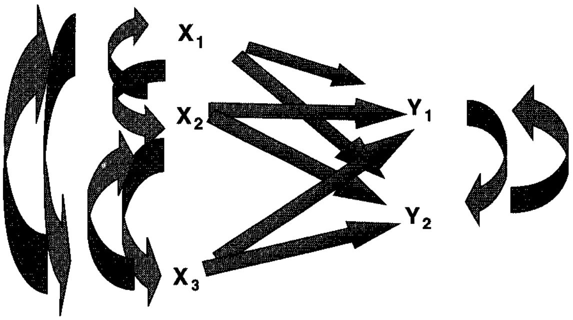

FIGURE 14.3.13 Dependence graph of two product parameters and four process parameters.

By using a special test procedure, the ascending order of the process parameters expressed by [·] can be determined:

$$X_{[3]}, X_{[4]}, X_{[5]}, X_{[1]}, X_{[2]}$$

The most important process parameter is X_2.

Numerical values for the process parameters are inserted in the process equation so that the calculated value of the product parameter Y_1 lies closer to the nominal value for Y_1. These values could be

$X_1 = -7$
$X_2 = 169$
$X_3 = 6.0$
$X_4 = 1.25$
$X_5 = 156.5$

Here we calculate for the product parameter Y_1 the value $\hat{Y}_1 = 1.03$ with the mean squared error of prediction = 0.36.

Using these settings for the process parameters we achieve new observations of the product parameter Y_1, which are illustrated in Fig. 14.3.14. The capability analysis of the improved process gives us the process capability indexes $C_p = 1.52$, $k = 0.06$ and $C_{pk} = 1.48$, which are higher than before the improvement. For this comparison we can also use the control charts for the product parameter Y_1. The charts before and after the improvement are represented in Figs. 14.3.15 and 14.3.16.

A comparison of the two Y-bar and range charts for the control of the given nominal values and tolerance limits in Figs. 14.3.15 and 14.3.16 reveals that many mean values of the subgroups lie outside the tolerance limits for the uncontrolled process and that all values lie

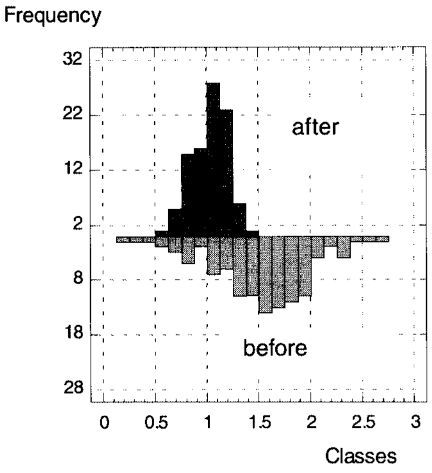

FIGURE 14.3.14 Frequency histogram for thermoshrinkage before and after control.

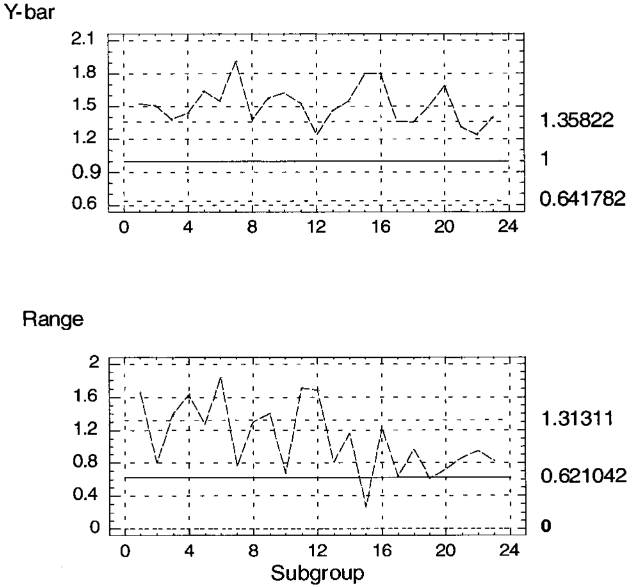

FIGURE 14.3.15 Control chart for the product parameter Y_1 for the uncontrolled process.

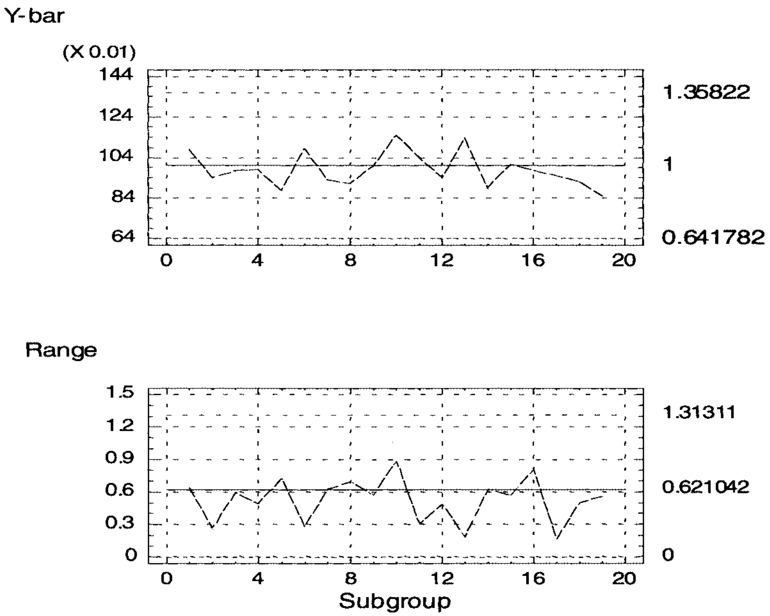

FIGURE 14.3.16 Control chart for the product parameter Y_1 for the controlled process.

inside the tolerance limits for the controlled process. The uncontrolled process is out of statistical control and the controlled process is in statistical control.

Justification of SPA

A complete SPA includes the structuring of a company as a network of processes, the improvement of the communication between processes, the improvement of the processes, the control of the processes, and the change of the organizational structure—which is necessary if the financial indexes are unsatisfactory, the quality of products is poor, costs are too high, and the price and performance index is too small.

The decision to apply SPA is based on the product capability indexes because conformance to the product parameters as well as parameters concerning the environment, legal requirements, and security must be considered as part of the decision.

Before the company invests in new machines or equipment, SPA should be implemented to determine the need for the investment, see Ref. [8]. A similar requirement is valid for the product and process development according to the principle that only known products or processes can be further developed, and in this development the known facts should be applied. The product and process equations represent these known facts and have to be used for the development in connection with a quality function deployment (QFD).

Time and Resources for Implementing SPA

The implementation of SPA will be conducted by a team consisting of the managers of the processes under consideration, together with workers in the processes and members of top management. The team will discuss the problem definition in a brainstorming session. In addi-

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tion, the implementation of SPA requires that the company be structured in appropriate manufacturing and service processes, and that modeling of these processes, with input data—process and product parameters related to each other—be completed. Following the data collection, the product and/or process capability indexes have to be calculated and a decision made if SPA can provide the solution to the problems. Thereafter, the models have to be computed and the results discussed by the team and practically applied. Support by a consultant can, in many cases, be beneficial. Computer programs are necessary. The authors have used Statgraphics Plus, version 7, for DOS by Manugistics.

The time needed for an SPA project depends on the number of processes in the network, the number of input variables, process and product parameters, sample size, the team, and decision makers. Based on experience, approximately half a year to one year will be required to complete a SPA project, by a team of 5 to 10 individuals working about 15 to 20 percent of their time on the project, and a consultant allocating 20 to 40 percent of his or her time. It is assumed that the project contains a network of less than five processes, each with about 10 product parameters, and about 50 to 70 input variables and process parameters.

Results of an SPA Application

One of the key results of the application of SPA is improved product quality. The quality reflects the conformance to all requirements and is measurable and can therefore be used for comparisons. Other important results include the improvement of the information flow (communication) between the processes by specified customer (internal or external) requirements as well as the proof of the conformance to the requirements of the finished products. Also, the process improvement through the control of the processes using the process equations and multivariate control charts are included. The change of the organizational structure from a hierarchical to a process-oriented structure, with defined objectives by the process owners, is another important result. Results of a more technical nature are the arrangement of input and process parameters, the selection of optimal subsets of input and process parameters, and the determination of the processes through measurements of input and process parameters. In particular, the measure of determination in connection with the capability indexes will show the process owner and the management that action may be needed to improve quality and productivity. As a by-product of these important results, an improvement of the financial indexes (for instance, an increase in productivity and a reduction of costs) will usually occur.

SUMMARY

The Impact of SPA on Process Design

Process design was defined as the structuring of a company in a network of manufacturing and service processes, the establishment of communications between the processes in the network by specifying customer (external and internal) requirements, the proof of the conformance to these requirements, and the control of the processes so that all requirements are satisfied and a change is made from the hierarchical to the process-oriented organization structure in which the main objectives—specification, control, proof—are given priority. SPA provides product equations for the specification of the customer requirements through nominal values and tolerance limits, process equations for the control of the processes, and process and product capability indexes to prove the conformance to the requirements. SPA supports the network of processes by summarizing the product parameters of the previous processes in a one-dimensional quantity, using the T^2-statistics by Hoteling and the realization of the transition of the products of the previous processes as inputs to the subsequent processes. SPA is therefore an important basis in the reorganization or relocation of plants [8].

Future Aspects of SPA

The increasing intensity of international competition and the growing industrial globalization will support broad applications of SPA in all branches of industry. The expected increase in financial indexes as a result of an application should convince management to invest in SPA. In accordance with Leibniz's theorem "*Theoria cum Praxi,*" an application of SPA will also advance general studies of SPA. Nevertheless, the research in the field of multivariate statistics is broader than the application. Therefore, by applying SPA, it will improve.

CONCLUSION

The need for SPA is apparent because SPA provides a unique possibility to improve communications between processes and product quality, in addition to increasing productivity and reducing costs. Data collection, problem definition, problem solving, mathematical calculations, organizational structuring, and information transfer are all part of the SPA concept. Consequently, SPA is a useful tool.

APPENDIX

In an analogy with a one-variant case, one develops the formulas for the multivariant capability indexes, which will be named *product capability indexes:*

$$PC_p = \frac{\text{vol(tolerance region)}}{\text{vol(variation region of the } m\text{-dimensional distribution)}}$$

$$= \frac{\prod_{j=1}^{m} (T_{u \cdot j} - T_{l \cdot j})\Gamma\left(\frac{m}{2}+1\right)}{\left(\pi \cdot \chi^2_{m \cdot 1-\alpha}\right)^{\frac{m}{2}} \cdot (\det \mathbf{S}_{YY})^{\frac{1}{2}}}$$

$$K = \sqrt{\frac{(\underline{\bar{Y}} - \underline{M}_{\mathrm{Y}})^{\mathrm{T}} \cdot \mathbf{T}_{\mathbf{YY}}^{-1} \cdot (\underline{\bar{Y}} - \underline{M}_{\mathrm{Y}})}{(\underline{T}_{\mathrm{u}} - \underline{M}_{\mathrm{Y}})^{T} \cdot \mathbf{T}_{\mathbf{YY}}^{-1} \cdot (\underline{T}_{\mathrm{u}} - \underline{M}_{\mathrm{y}})}}$$

and

$$PC_{pk} = (1 - K) \cdot PC_p$$

where m = the dimension of the vector of product parameters $\underline{Y}^T = (Y_1, \ldots, Y_m)$ and

$\underline{T}_l^T = (T_{l.1} \ldots T_{l.m})$

$\underline{T}_u^T = (T_{u.1} \ldots T_{u.m})$

$\underline{M}_Y^T = (M_1 \ldots M_m)$

$$\mathbf{T}_{\mathbf{YY}} = Diag\left(\frac{T_{u.j} - T_{l.j}}{6}\right) \cdot \mathbf{R}_{\mathbf{YY}} \cdot Diag\left(\frac{T_{u.j} - T_{l.j}}{6}\right)$$

$\mathbf{S}_{\mathbf{YY}}$ the sample covariance matrix and $\mathbf{R}_{\mathbf{YY}}$ is the sample correlation matrix of the vector of the product parameters Y.

DECISIONS: On the basis of the product capability indexes, the same decisions as represented in Fig. 14.3.2 have to be made, namely:

- If $PC_p < 1$, then the process is out of control and hence has to be improved in such a way that the variation of the product parameters is reduced.
- If $PC_p > 1$ and $PC_{pk} < 1$, then the process is also out of control and needs to be improved by centering the process in such a way that the vector of the mean values is in close vicinity to the vector of the nominal values of all product parameters.
- If $PC_p > 1$, and $PC_{pk} > 1$, then the process is in statistical control.

Therefore, the sample covariance matrix

$$\mathbf{S_{YY}} = \begin{pmatrix} 0.22495 & 0.00353 & -0.10751 & -0.00455 \\ & 0.04206 & 0.04239 & -0.00081 \\ & & 0.24588 & 0.01654 \\ & & & 0.00882 \end{pmatrix}$$

and the vector of the differences between the upper and lower tolerance limits

$$(T_u - T_l)^T = (1.8 \;\; 0.6 \;\; 1.2 \;\; 0.4)$$

using the product capability formulas gives us

$$PC_p = \frac{(1.8 \cdot 0.6 \cdot 1.2 \cdot 0.4) \cdot 2}{(\pi \cdot 16.2512)^2 \cdot 0.003169} = 0.126$$

The correction factor K can be computed using the formulas

$$Diag\left(\frac{T_{u.j} - T_{l.j}}{6}\right) \cdot \mathbf{R_{YY}} \cdot Diag\left(\frac{T_{u.j} - T_{l.j}}{6}\right)$$

$$\mathbf{T} = \begin{pmatrix} 0.3 & & & \\ & 0.1 & & \\ & & 0.2 & \\ & & & 0.0667 \end{pmatrix} \cdot \begin{pmatrix} 1 & 0.036 & -0.457 & -0.102 \\ & 1 & 0.416 & -0.042 \\ & & 1 & 0.355 \\ & & & 1 \end{pmatrix} \cdot \begin{pmatrix} 0.3 & & & \\ & 0.1 & & \\ & & 0.2 & \\ & & & 0.0667 \end{pmatrix}$$

$$= \begin{pmatrix} 0.09 & 0.00108 & -0.02742 & -0.002041 \\ & 0.01 & 0.00832 & -0.0002801 \\ & & 0.04 & 0.004735 \\ & & & 0.0044488 \end{pmatrix}$$

$$T^{-1} = \begin{pmatrix} 15.5575 & -14.2068 & 14.7379 & -9.44534 \\ & 140.235 & -44.8315 & 50.0345 \\ & & 50.3007 & -49.6051 \\ & & & 276.395 \end{pmatrix}$$

Here we get

$$(\mathbf{T_u} - \mathbf{M}_Y)^T \cdot \mathbf{T^{-1}} \cdot (\mathbf{T_u} - \mathbf{M}_Y) = 37.1915$$

$$(\overline{\mathbf{Y}} - \mathbf{M}_Y)^T \cdot \mathbf{T}^{-1} \cdot (\overline{\mathbf{Y}} - \mathbf{M}_Y) = 3.62263$$

and

$$K = \sqrt{\frac{(\underline{\overline{Y}} - \underline{M}_Y)^T \cdot \mathbf{T}_{\mathbf{YY}}^{-1} \cdot (\underline{\overline{Y}} - \underline{M}_Y)}{(\underline{T}_u - \underline{M}_Y)^T \cdot \mathbf{T}_{\mathbf{YY}}^{-1} \cdot (\underline{T}_u - \underline{M}_Y)}} = \sqrt{\frac{3.62263}{37.1915}} = 0.31$$

so that

$$PC_{pk} = (1 - K)\ PC_p = 0.07$$

DECISION: The process for manufacturing plastic case components cannot be monitored statistically. The process has to be improved. Because $PC_p < 1$ and therefore $PC_{pk} < 1$, the process has to be improved in such a way that the variability of the product parameters is reduced and the nominal values and the mean values of the product parameters coincide.

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BIOGRAPHIES

Walter Jahn received his education from the School of Forestry, Germany, and worked for the school until 1960. He studied mathematics from 1964 until 1968 and graduated as Dr. rer. nat in mathematics. Jahn worked at the University of Leipzig, Germany, as a university lecturer and scientist until 1993, and is the author of four scientific books and many scientific articles. He has 30 years of experience in the research and application of the multivariate statistical procedures. Since 1994, Jahn has worked as a freelance consultant on fields control in processes, improvement of processes, and networks of processes using the multivariate statistical procedures.

Dieter E. Löhr is presently international coordinator of manufacturing technology at WOCO Unternehmungsgruppe (Business Group) in Germany. He is Diplomingenieur (FH), mechanical engineering. Löhr has 30 years of experience in the rubber industry in a variety of positions: developer of tire manufacturing technology, production manager, plant manager, project manager for a new manufacturing factory in the United States, project manager for building a technical center for automobile tests, operations manager for multiplant manufacturing of rubber to metal parts and molded products, and project manager for consolidating three plants into one. He spent several years in the United States in a joint venture, Lord-Metzeler Automotive, Inc.

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Willi Richter is presently the leader of the consulting group Richter & Partner. The functional experience of the group encompasses manufacturing, industrial engineering, process and product development, production transfer, and process improvement. Richter is Diplomwirtschaftsingenieur. He has specialized training in MOST and has 30 years of experience in the application of MOST and the relocation of plants. He worked on projects building a technical center for automobile tests and consolidating three plants into one.

CHAPTER 14.4

MANUAL AND AUTOMATED ASSEMBLY

Jack Walker
The Jack Walker Group
Merritt Island, Florida

The influence of product design on the manufacturing assembly task is discussed. The decision to automate or hand-assemble a product should be made during product design, and followed by a process plan with methods, motion analysis, and standards. Manual assembly techniques are introduced, including assembly aids and hand tools. Automation is presented as a choice of soft or hard systems, with discussions of the several automation choices. Electrical and electronic assembly techniques are outlined. The industrial engineer's role is stressed in these discussions.

ASSEMBLY BACKGROUND

It is sometimes hard to remember that the real purpose of manufacturing a product is to make money! Regardless of the product line, we must always provide complete customer satisfaction with our quality products and on-time delivery. Our concentration, therefore, should be on the *lowest-cost methods* available to achieve these results.

About three-fourths of the 6 million firms in the United States have less than 10 employees, almost one-fourth have up to 100 employees, and only 2 percent have more than 100 employees. At Boeing, the largest U.S. aerospace company, about 5 to 7 percent of their cost is in assembly; at Ford, about 10 to 12 percent is assembly cost. This assembly percentage increases with the smaller firms until we reach the one-man company where purchases, parts fabrication, and assembly may each be about one-third of the cost.

Perhaps we should examine a one-person business operation where the owner makes the parts, assembles them, and does the finish testing, painting, packing, and delivery. The difference between total income and the amount of money spent during the month is *salary,* or *profit.* Of course, there may be rent on a building, raw materials and supplies, and payments on equipment and machines. OK, let's deduct these, and now we have profit. Whoops—there is probably heating, lighting, insurance of some type—and taxes—and now the remainder is profit. We can see that even in the one-person factory, real cost is not so easy to determine.

As business improves, one person cannot do everything by working at a faster pace or putting in longer hours. The owner must take action in order to maintain quality and on-time delivery. One option is to add helpers and continue to perform all the operations in-house. Another choice is to buy the parts and continue to perform the assembly operation in order to maintain control of the final product quality and delivery schedule. It will still be "his or her" product as far as keeping customers satisfied. As growth continues, review of the product design is probably in order—it may not be the best design for assembly. One of the next steps is to optimize the process and flow through the plant. At higher production rates or product complexity, the addition of automated screwdrivers, nut runners, riveters, spot-welding heads, and the like will be considered. The addition of transfer devices may be a logical improvement for moving parts from the fabrication or receiving departments to assembly stations, as well as for the transfer of parts and subassemblies down the production line.

Starting with a one-person operation, the small firm has now grown to a multiemployee company using many of the same techniques that were successful in the beginning, but now improved to permit handling the increased business. In the end, the assembly process may well become the key to continuing success.

Assembly always consists of mechanical operations, whether the product is made of metal, plastic, wood, or electronic components. The operations can be performed manually, automatically, or integrated in some manner using a combination of systems.

When production rates are high enough, and the forecast for continuing production looks solid, some assembly operations can be performed automatically with special-purpose machines. A part or an assembly whose requirements exceed 200,000 should be considered for automation. When the quantity exceeds 1 million, it is almost certain that automation must be used.

PRODUCT DESIGN FOR ASSEMBLY

The analysis of a product design for ease of assembly depends to a large extent on whether the product is to be assembled manually, with special-purpose automation, with general-purpose automation (robots), or with a combination of these. The problems inherent in automatic feeding and orienting parts requires close attention to dimensions and tolerances, with little variation allowed from part to part. The human operator's hands have infinite control and flexibility to compensate for the many variations encountered in manufacturing processes. The automatic assembly machine can produce quality and quantity of parts only under strict, inflexible parameters. The ability to adapt automation to assembly depends largely on the detail design of the individual elements and their complexity.

There is no magic formula for guiding the design team of a new or redesigned product, or for the support by members of the team representing the factory. There are, however, techniques and guides for (1) examining the customer's wants and needs, (2) working together as an integrated team for product design, (3) identifying the problems with assembly of the final product, and (4) developing the product cost. Figure 14.4.1 shows how a small investment in good design by Ford Motor Company has the greatest leverage on final product cost by saving money in materials, work-in-process, warehousing, and floor space. Good credos to follow when attacking the final design details are:

- Design must perform the intended function.
- Production rate influences decisions.
- Market life of the product establishes total quantity.
- Design by subtraction—not by addition. If an element is not really necessary, leave it out.
- Design by combination—not by separation. Eliminate parts by combining two or more.
- Use proven design approaches. Do not blaze new trails at the frontiers of technology.
- Seek out and use commercially proven methods. Observe what other firms are doing.

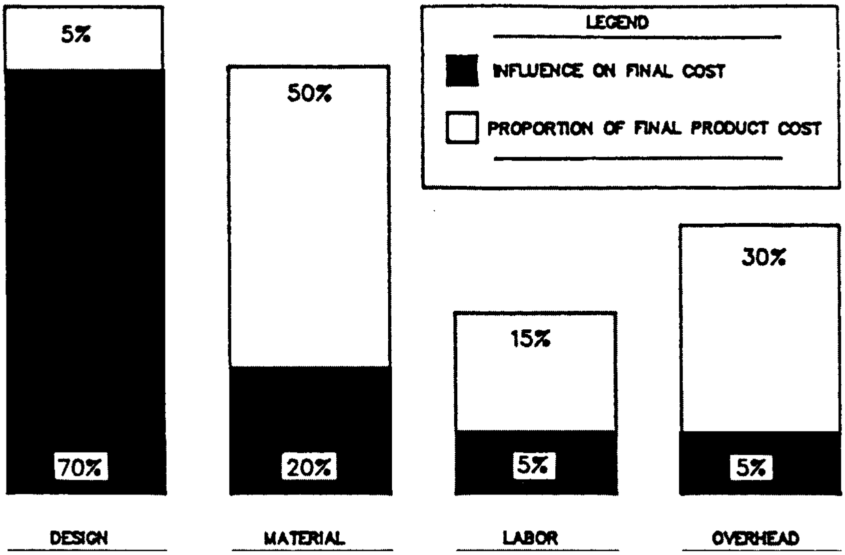


FIGURE 14.4.1 The cost of design in manufacturing at Ford. *(Courtesy of Ford Motor Company.)*

Design for Manual Assembly

Geoffery Boothroyd, in his book *Product Design for Manufacture and Assembly* (Marcel Dekker, New York, 1994), has developed a few general design guidelines as a result of his experience in applying design for assembly (DFA) and design for manufacture and assembly (DFMA) techniques. Guidelines do not provide a quantitative evaluation tool, a ranking as to which offer the greatest improvement in handling and assembly, or a way to estimate the improvement resulting from the elimination of a part. However, guidelines do provide the designer with suitable background information to be used to develop a design that will be more easily assembled than a design developed without such information. The author recommends Boothroyd's *Product Design for Manufacture and Assembly* handbook, which provides the means of quantifying the elements of assembly difficulty.

The process of manual assembly can be divided naturally into two separate areas: (1) *handling* (acquiring, orienting, and moving the parts) and (2) *insertion and fastening* (mating a part to another part or group of parts). It is always necessary to use manual assembly costs as a basis for comparison of various design elements. Even when automation is being seriously considered, some operations may have to be carried out manually, and it is necessary to include the cost of these operations in the analysis.

Design Guidelines for Manual Part Handling

Following are design guidelines for manual part handling. See Fig. 14.4.2.

- Design parts that have end-to-end and rotational symmetry about the axis of insertion.
- Design parts to be obviously asymmetric when they cannot be made symmetric.
- Design features that will prevent jamming of parts that tend to nest or stack when stored.
- Avoid features that will allow tangling of parts.
- Avoid parts that stick together or are slippery, delicate, flexible, very large or small, or that are hazardous to the handler.

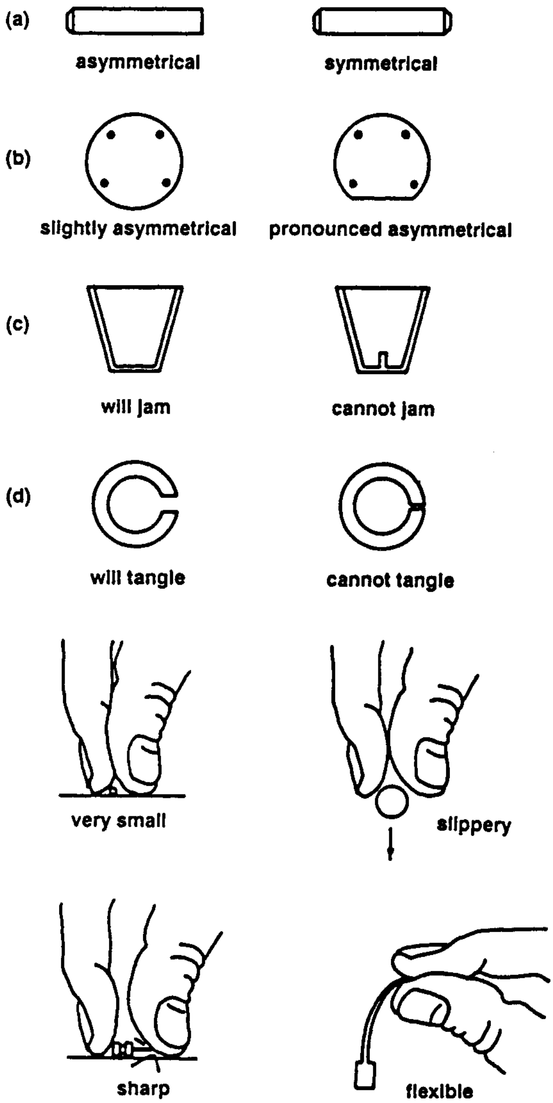

(a)
asymmetrical
symmetrical
(b)
slightly asymmetrical
pronounced asymmetrical
(c)
will jam
cannot jam
(d)
will tangle
cannot tangle
very small
slippery
sharp
flexible

FIGURE 14.4.2 Features affecting part handling.

Design Guidelines for Manual Insertion and Fastening

Following are design guidelines for manual insertion and fastening.

- Design so that there is little or no resistance to insertion and provide chamfers to guide insertion of two mating parts.
- Standardize by using common parts, processes, and methods across all models and even across product lines.

- Use pyramid assembly—provide for progressive assembly about one axis of reference. In general, it is best to assemble from above.
- Avoid the necessity for holding parts down to maintain their orientation during manipulation or placement of another part.
- Design so that a part is located before it is released.

Design for Automatic Assembly

Parts are usually introduced to an assembly machine as bulk components. They are placed in a hopper and tracked to a loading station. Whether the hopper is vibratory, rotary, or oscillatory, it relies on gravity and/or friction for part movement. Some sort of gating or orientation device allows only those parts in the proper attitude or position to enter the track.

Efficiency is affected by the system used. Nonvibratory feeders, for example, are limited in the number of orientations they can perform. Part geometry is a critical factor. Soft parts may tangle in the hopper. Bowl driving forces may distort parts to the point where orienting in the bowl is impossible. Distortion of parts due to stacking and handling can also cause serious difficulty. Parting line flash from cast and molded parts is an example of a problem that never appears on a print. The sensitivity of the part to moisture, static electricity, and residual magnetism may not become apparent until mechanical handling is attempted. Sometimes, a particular surface may be declared critical and must be protected for subsequent operations. This situation may preclude or restrict the use of automatic feeding methods. Use of symmetry in part design makes orientation either unnecessary (ball bearings, etc.) or very simple (plain rods, disks, etc.). Asymmetrical parts can sometimes be made symmetrical, and the added manufacturing cost is often insignificant when compared with orientation and sensing costs involved during assembly.

Some general rules for design of products and parts for ease of automatic assembly include the following:

- Minimize the number of parts.
- Ensure that the product has a suitable base part on which to build the assembly.
- Ensure that the base part has features that will enable it to be readily located in a stable position in the horizontal plane.
- Design the part so that it can be built up in layer fashion, each part being assembled from above.
- Provide chamfers or tapers that will help to guide and position parts.
- Avoid projections, holes, or slots that will cause tangling in the bulk feeders.

The following techniques simplify, improve, and in some cases make feeder orientation possible:

Minimize the number of different orientations. Vibratory feed rates depend on successful orientation. For instance, if the track feed rate is 600 pieces per minute and the orientation probability is only 1 in 10, we are effectively limited to 60 pieces per minute for assembly.

Avoid parts that tangle. Springs are probably the best example. For instance, a simple open-coil spring may be redesigned with close-wound coils at both ends and in the center. This design often permits handling by conventional hoppers and feed systems.

Avoid using parts that nest, shingle, or climb. Matching tapered surfaces will cause parts to lock or nest. Internal ribs, projections, or increasing the angle well above the locking angle will avoid the problem.

Determine critical tolerances. It is essential to determine dimensions that are critical for proper parts feeding and yet may be noncritical for piece-part function if the parts feeding operation is to remain trouble-free.

Assume for now that parts are oriented and coming down the feeder track; the job is now half done. There are, however, additional important design considerations if parts are to be successfully integrated in a trouble-free assembly operation.

Design parts for easy assembly. Design parts with guides for proper location during assembly. Clearances should be carefully considered, and the liberal use of chamfers and radii will allow the parts to fall together in place unassisted. Sufficient clearance should be allowed for feeder fingers or other tooling needed to handle the parts.

When parts pose unusually difficult handling and orientation problems, experimental mock-up stations should be built to verify parts handling processes prior to building the assembly machine. The product designer, the manufacturing engineer, and the tool designer should work as a team through this development state.

In designing for automatic assembly, the designer should ask the following questions:

- Can parts be made symmetrical to avoid orientation problems?
- Do symmetrical parts have clearly defined polarity features?
- Are the number of significant part orientations minimized?
- Will parts tangle?
- Will parts nest or interlock, thereby causing problems?
- Will the part design cause shingling?
- Are critical dimensions and tolerances clearly defined?
- Do the parts lend themselves to easy location and assembly?
- Does the design have a datum surface for accurate parts location during assembly?
- Have all unnecessary handling requirements, such as turning over parts and/or assemblies, been avoided?
- Does the assembly have components that are buried or difficult to reach and position?
- Has the design been simplified and standardized as much as possible?
- Have excessive burrs and flash been eliminated?
- Can difficult-to-handle parts be assembled in an automatic system?

PLANNING THE ASSEMBLY PROCESS

Planning for assembly should include an assembly process summary or process routing, detailed work instructions for each operation identified in the summary, an operations parts list for each operation, process sketches or visual aids, and a workplace layout for each operation. The work instructions should call out all tools that are necessary to perform the operation, and there should be a standard time on the process summary for each operation called out, broken down to the level of setup and run times.

The Flow Process Chart

Recording of the job details can best be accomplished through the use of process chart techniques, specifically the *flow process chart* and the *flow diagram.* The flow process chart is a device for recording each step of a job in a compact manner, as a means of better understanding it and improving it. The chart represents graphically the separate steps of the events that occur during the performance of work, or during a series of actions. The process chart may be used to record the flow within a unit, a section, a department, or between departments. It may show in sequence the total activity of a production operator, or it may show in sequence the steps that the worker, part, or material goes through. The chart can be either the operator type or the material type, but not a combination.

Analysis of such a chart, giving a graphic picture of every step in the process, is almost certain to suggest improvements. Some operations can be eliminated; a portion of an operation can be eliminated; one operation can be combined with another; better routes for the parts can be found; more economical machines can be used; delays between operations can be eliminated, all of which go to produce a better product at a lower cost.

To make a flow process chart requires careful adherence to the following rules. See Fig. 14.4.3.

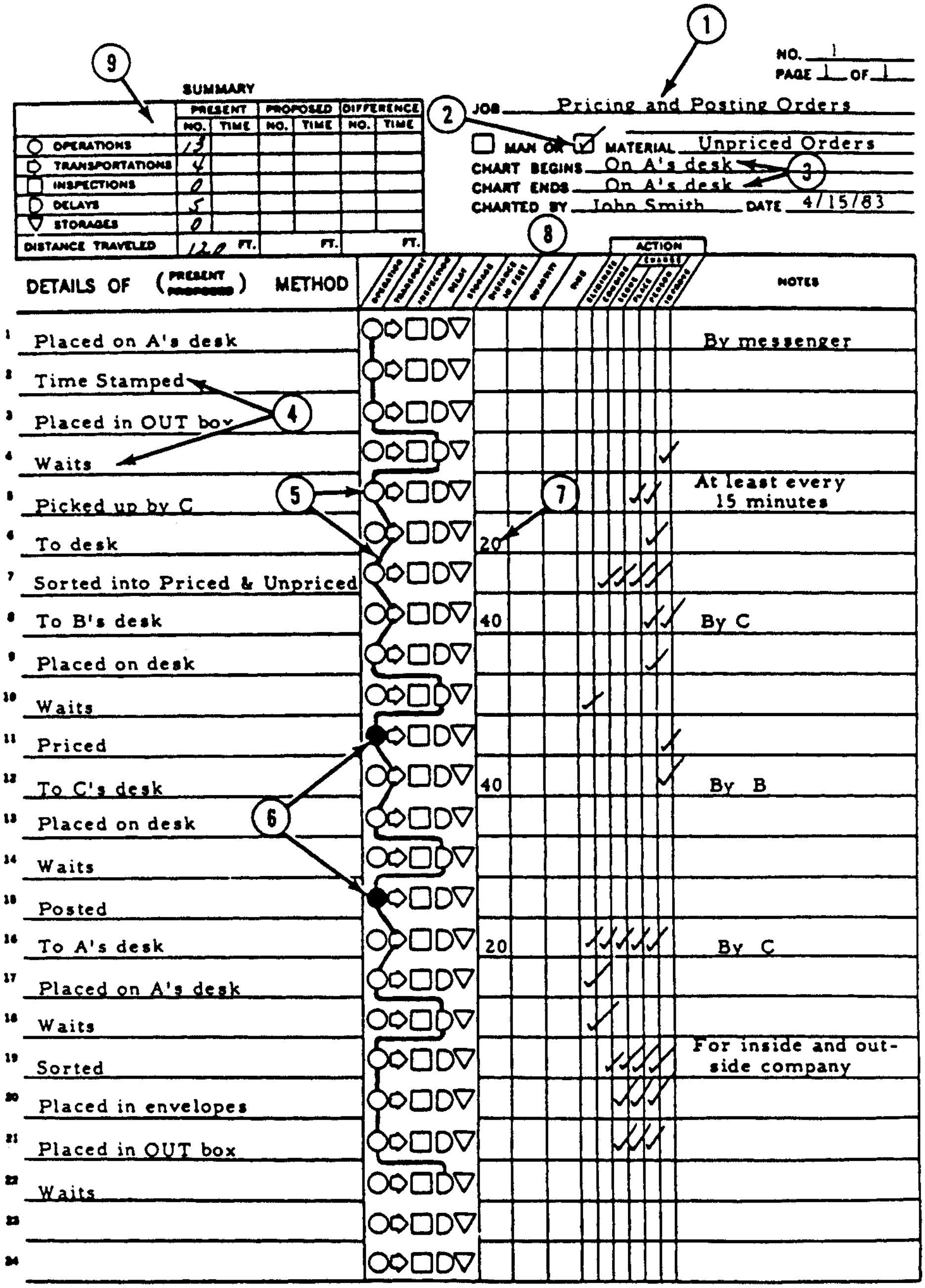
1. *State the activity being studied.* Make certain you are really naming the activity you have chosen to study.
2. *Choose the subject to follow.* Decide on a person or a material, and follow him, her, or it through the entire process.
3. *Pick a starting and ending point.* This is to make certain that you will cover all the steps you wish to cover, but no more or less.
4. *Write a brief description of each detail.* Step-by-step—no matter how short or temporary.
5. *Apply the symbols.* The description determines each symbol. Draw a connecting line between each of the proper symbols.
6. *Identify the "do" operation.* Shade in the symbols for these operations to help you later in your analysis when you begin challenging.
7. *Enter distances.* Whenever there is a transportation, enter the distance traveled.
8. *Enter time if required.* Many times this is not necessary at this point. However, if it will help, note the time required or elapsed.
9. *Summarize.* Add up all of the facts and put them in the summary block. The summary should indicate the total number of operations, transportations, inspections, delays, storages, and distances traveled.

Workstations

Workstation layouts are important for defining the assembly method. They are usually in the form of a plan view of the workstation, and show the location of tooling and fixturing, parts bins, work instructions, incoming work staging, placement of completed work, and any other information pertinent to the operation and the setup of the workstation. See Fig. 14.4.4 for an example.

Line layouts are used where progressive assembly lines are to be used to build the product, but the plant layout drawings do not show which workstation goes where. These are used by supervision to set up the line to conform to the assembly process flow. See Fig. 14.4.5.

If the plant is a high-volume producer of a single product line, detailed assembly work instructions may be unnecessary. Once operators are trained to perform a short-cycle assembly operation, little else is needed except possibly some clear, concise visual aids showing the critical details of the operation in a pictorial or exploded view form. However, the industrial engineer (by whatever name in your firm) must plan such production down to the most detailed level. He or she must prepare a layout of the assembly lines, show each workstation setup, define the assembly tools required, and write a complete description of the work to be performed at each station on the line. The industrial engineer can then establish standard



NO. 1
PAGE 1 OF 1

JOB Pricing and Posting Orders

☐ MAN OR ☑ MATERIAL Unpriced Orders

CHART BEGINS On A's desk

CHART ENDS On A's desk

CHARTED BY John Smith DATE 4/15/83

SUMMARY

	PRESENT NO.	PRESENT TIME	PROPOSED NO.	PROPOSED TIME	DIFFERENCE NO.	DIFFERENCE TIME
○ OPERATIONS	13					
➪ TRANSPORTATIONS	4					
☐ INSPECTIONS	0					
D DELAYS	5					
▽ STORAGES	0					
DISTANCE TRAVELED	120 FT.		FT.		FT.	

	DETAILS OF (PRESENT ~~PROPOSED~~) METHOD	DISTANCE IN FEET	NOTES
1	Placed on A's desk		By messenger
2	Time Stamped		
3	Placed in OUT box		
4	Waits		
5	Picked up by C		At least every 15 minutes
6	To desk	20	
7	Sorted into Priced & Unpriced		
8	To B's desk	40	By C
9	Placed on desk		
10	Waits		
11	Priced		
12	To C's desk	40	By B
13	Placed on desk		
14	Waits		
15	Posted		
16	To A's desk	20	By C
17	Placed on A's desk		
18	Waits		
19	Sorted		For inside and outside company
20	Placed in envelopes		
21	Placed in OUT box		
22	Waits		
23			
24			

FIGURE 14.4.3 Flow process chart example.

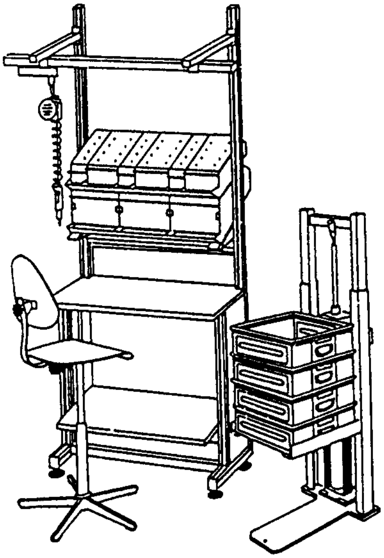
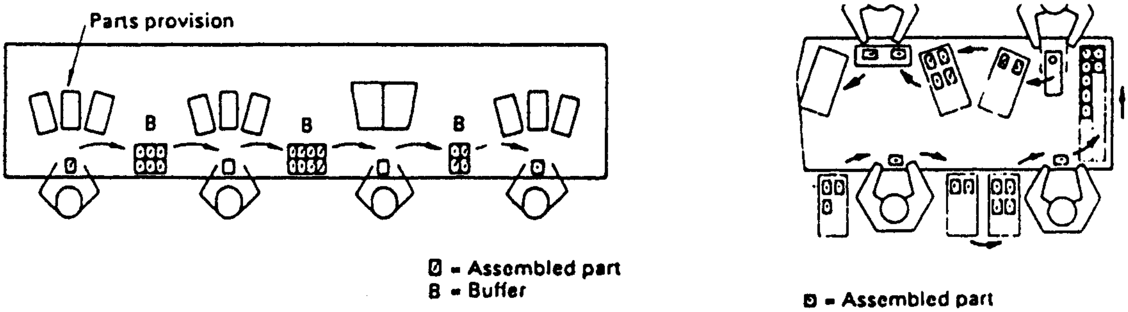


FIGURE 14.4.4 Assembly workbench arrangement as it would appear on the shop floor.

times, decide where visual aids are needed and prepare them, fine-tune or balance the line, assist in training operators, and finally shake down or debug the line.

If the company manufactures a variety of different product lines, in medium to high volumes, and/or sets up and produces to a job-order-type system, assembly process documentation that is complete and to the greatest level of detail is especially important. Good assembly process planning and documentation significantly reduces operator learning (and relearning) time. The assembly process documentation package is essential to the operation of ongoing production control and cost collection systems. The assembly process routing provides the steps or sequences that materials, parts, assemblies, and work-in-process must follow to build the product. It provides the time standards for each operation, and the assembly parts list for each operation provides the information needed by production control to pull and kit material for production.



(a) (b)

FIGURE 14.4.5 Manual line assembly with manual transfer of the workpieces (*a*) in a line arrangement and (*b*) in rectangular form. *(Courtesy IPA Stuttgart.)*

In a small plant, where production runs may be small to nonexistent, assembly process planning with only minimum documentation is required and can be justified for the reasons mentioned earlier. Even in the case where no formal production control system exists and the production supervisor draws material from the stockroom in one batch issue for the entire job, pictorial visual aids, workstation layouts, a tool list, and an assembly process routing should be provided.

In developing the manufacturing process for assembly, the industrial engineer must specify the most economical methods for the job. To do this, he or she must apply the fundamental techniques of methods analysis, motion economy, and work simplification. If manual assembly is employed, an operator can adapt to changing conditions such as those brought about by part variation, mislocation, and product model mix. An operator can compensate for these changing conditions and, as a result, may not require elaborate tools and fixtures to perform the assembly tasks. Operator error and fatigue can result in quality problems, which may require specific, detailed work instructions to control the manual assembly operations.

MANUAL ASSEMBLY

Manufacturing Methods Analysis

The industrial engineer must specify the most economical methods for the job in developing the assembly process. To do this, the industrial engineer must understand and be able to apply the fundamental techniques of methods analysis, motion economy, and work simplification.

Even the best and most thorough planning will sometimes overlook details, or specify methods that can be improved upon later after the product is in production. Part of the job of the industrial engineer is to be alert for these opportunities to improve the process and the flow.

Principles of Motion Economy

The following discussion is to explore the rules or principles of motion economy that have been used successfully in manufacturing methods studies. These principles form a basis, code, or body of rules that, if applied correctly, make it possible to greatly increase the output of manual factory labor with a minimum of fatigue. These principles will be examined under the subdivisions of *operator* tasks, the *workplace,* and as applied to *tools and equipment.*

Operator Motion Economy. The principles of motion economy as related to the tasks of the operator are as follows:

- The two hands should begin as well as complete their motions at the same time.
- The two hands should not be idle at the same time except during rest periods.
- Motions of the arms should be made in opposite and symmetrical directions and should be made simultaneously.

These three principles are closely related and should be considered together. It seems natural for most people to work productively with one hand while holding the object being worked on with the other hand. This is extremely undesirable, and should be avoided. The two hands should work together, each beginning a motion and completing a motion at the same time. Motions of the two hands should be simultaneous and symmetrical.

Many kinds of work can be accomplished better using both hands than by using one hand. For most manufacturing assembly operations, it is advantageous to arrange similar work on the left- and right-hand sides of the workplace, thus enabling the left and right hands to move together, each performing the same motions. The symmetrical movements of the arms tend to balance each other, reducing the shock and jar on the body and enabling the operator to perform the task with less mental and physical effort. There is apparently less body strain when the hands move symmetrically than when they make nonsymmetrical motions, because of balance.

The fourth principle of motion economy states that hand and body motions should be confined to the lowest classification with which it is possible to perform the work satisfactorily. Studies of hand motions emphasize that material and tools should be located as close as possible to the point of use. The motions of the hands should be as short as the work permits. In listing the five general classifications of hand motions, the one requiring the least amount of time and effort is shown first:

1. Finger motions
2. Motions involving fingers and wrist
3. Motions involving fingers, wrist, and forearm
4. Motions involving fingers, wrist, forearm, and upper arm
5. Motions involving fingers, wrist, forearm, upper arm, and shoulder (causes posture change)

However, it should be pointed out that finger motions have been found to be less accurate, slower, and more fatiguing than motions of the forearm. Evidence seems to indicate that the forearm is the most desirable member for performing light work. In highly repetitive work, motions about the wrist and elbow are superior to those of the fingers or shoulders.

The fifth principle of motion economy states that momentum should be employed to assist the worker wherever possible, and it should be reduced to a minimum if it must be overcome by muscular effort. The momentum of an object is defined as its mass times its velocity. In the factory environment, the total weight moved by the operator may consist of the weight of the material moved, the weight of the tools moved, and the weight of the part of the body moved. It should be a real possibility to employ momentum to advantage when a forcible blow or stroke is required. The motions of the worker should be so arranged that the blow is delivered when it reaches its greatest momentum.

The sixth principle of motion economy states that smooth, continuous, curved motions of the hands are preferable to straight-line motions involving sudden and sharp changes in direction. Abrupt changes in direction are not only time consuming but also fatiguing to the operator.

The seventh principle of motion economy states that ballistic motions are faster, easier, and more accurate than restricted or controlled movements. Ballistic movements are fast, easy motions caused by a single contraction of a positive muscle group, with no antagonistic muscle group contracting to oppose it. A ballistic stroke may be terminated by the contraction of opposing muscles, by an obstacle, or by dissipation of the momentum of the movement, as in swinging a sledge hammer. Ballistic movements are preferable to restricted or controlled movements, and should be used whenever possible.

The eighth principle of motion economy states that work should be arranged to permit an easy and natural rhythm wherever possible. Rhythm is essential to the smooth and automatic performance of any operation. Rhythm, as in a regular sequence of uniform motions, aids the operator in performing work. A uniform, easy, and even rate of work are aided by proper arrangement of the workplace, tools, and materials. Proper motion sequences help the operator to establish a rhythm, which helps make the work a series of automatic motions, where the work is performed without mental effort.

The ninth principle of motion economy states that eye fixations should be as few and as close together as possible. Where visual perception is required, it is desirable to arrange the task so that the eyes can direct the work effectively. The workplace should be laid out so that the eye fixations are as few and as close together as possible.

Workplace Motion Economy. Workstation layouts are important from the standpoint of assembly operator methods. Layouts are usually in the form of a plan view of the workstation, and show where tooling and fixturing should be placed, where parts bins should be placed, work instructions, tote pans for staging incoming work, for placing completed work, and any other information pertinent to the operation and the setup of the workstation. They tell the assembly supervisor how to set up and configure the individual workstations for optimum productivity and flow of work.

Line layouts are used where progressive assembly lines are to be used to build the product, and the plant layout drawings do not show which workstation goes where. These are used in setting up the line to conform to the assembly process flow, and to ensure optimum methods and work flow.

The first principle of motion economy related to the workplace states that there should be a definite and fixed place for all tools and materials. The operator should always have tools and materials in the same location, and finished parts and assembled units should be placed in fixed positions or locations. For example, in the assembly of mechanical hardware, the hand should move without mental direction to the bin containing flat washers, then to the bin containing lock washers, then to the bin containing bolts, and finally to the bin containing hex nuts. There should be no thinking required on the part of the operator to do any of this.

The second principle of motion economy related to the workplace states that tools, materials, and controls should be located close to the point of use. In the horizontal plane, there is a definite and somewhat limited area that the worker can use with a normal expenditure of effort. This includes a normal working area for the right hand and one for the left hand for each working separately, and another for both hands working together. Figure 14.4.6 shows this and the dimensions of normal and maximum working areas in the horizontal and vertical planes. Both the standing and sitting positions are included. It also shows normal bench work surface heights, which can have a significant adverse effect if they are not correct.

Figure 14.4.7 shows in greater detail the areas of easiest reach for the left and right hands, for both hands working together, and the area in which small objects can be most easily picked up.

The third principle of motion economy related to the workplace states that gravity-feed bins and containers should be used to deliver the material close to the point of use. This can sometimes be accomplished by using parts bins with sloping bottoms, which feed parts by gravity to the front of the bin, eliminating the need for the assembly operator to reach down into the bin to grasp parts.

The fourth principle of motion economy related to the workplace states that drop deliveries should be used wherever possible. This requires configuring the workplace, for example, so that finished units may be disposed of by releasing them in the position in which they are completed, delivering them to their next destination by gravity. Besides the savings in time, this frees the two hands so that they may begin the next cycle immediately without breaking the rhythm.

The fifth principle of motion economy related to the workplace states that materials and tools should be located to permit the best sequence of motions.

The sixth principle of motion economy related to the workplace states that provision should be made for adequate lighting.

The seventh principle of motion economy related to the workplace states that the height of the workplace and chair should be arranged so that alternate sitting and standing at work are easily possible.

The eighth principle of motion economy related to the workplace states that a chair of the type and height to permit good posture should be provided for the operator.

Tools and Equipment. Principles of motion economy as related to the design of tools and equipment include the following:

- The hands should be relieved of all work that can be done more effectively by a jig, fixture, or foot-operated device.

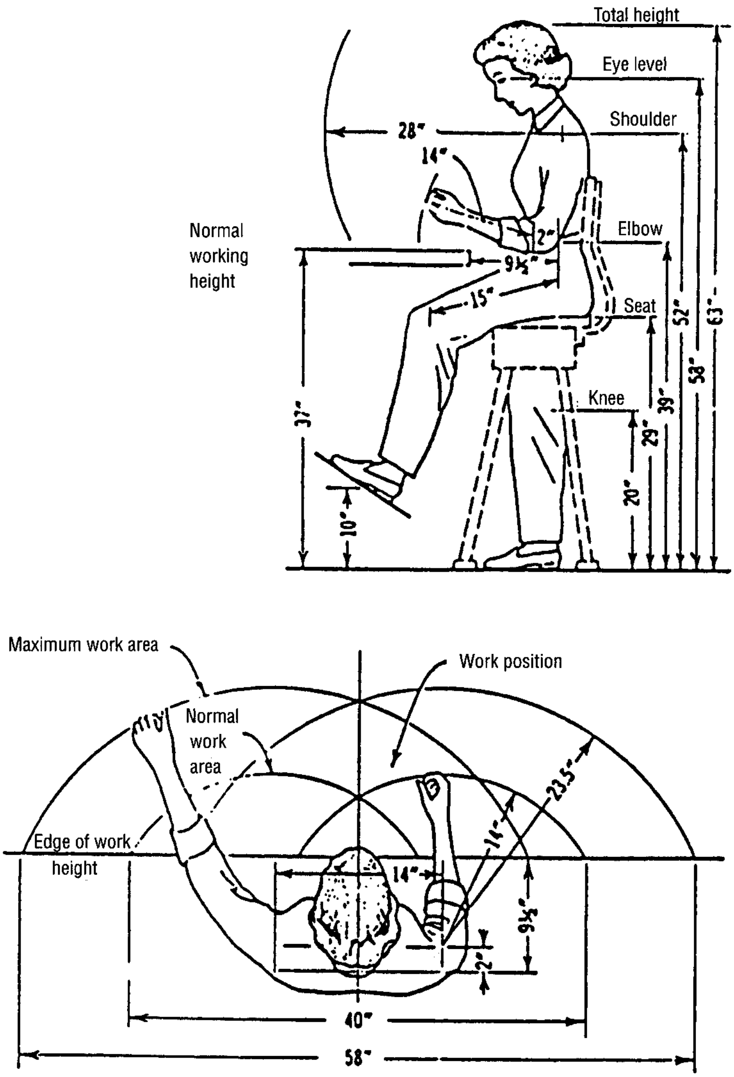
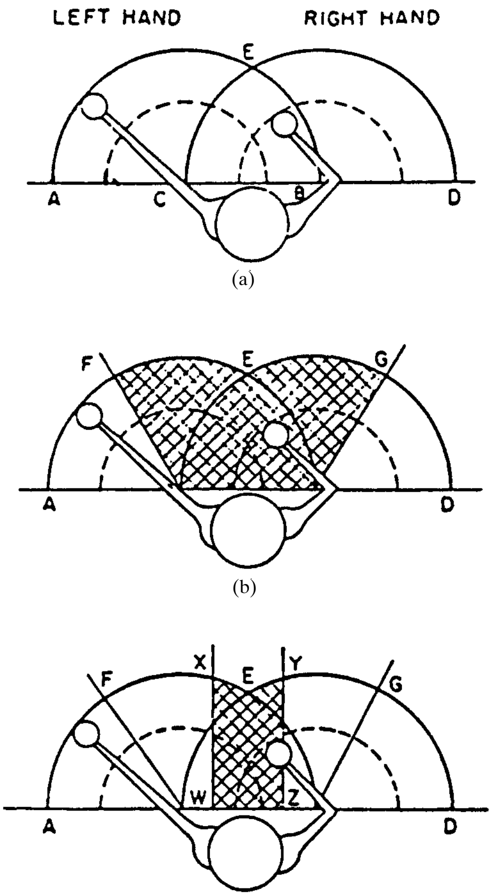

Total height
Eye level
Shoulder
Elbow
Seat
Knee
28"
14"
2"
9½"
15"
Normal working height
37"
10"
20"
29"
39"
52"
58"
63"
Maximum work area
Work position
Normal work area
Edge of work height
23.5"
14"
14"
9½"
2"
40"
58"

FIGURE 14.4.6 Normal and maximum working areas and heights.

- Two or more tools should be combined wherever possible.
- Tools and materials should be prepositioned whenever possible.
- Where each finger performs some specific movement, the load should be distributed in accordance with the inherent finger capacities (arrangement of keyboard keys).
- Levers, crossbars, and handwheels should be located in such positions that the operator can operate them with the least change in body position and with the greatest mechanical advantage.



(a)

(b)

(c)

FIGURE 14.4.7 Areas of easiest reach for each hand, and for both hands working together. (*a*) Maximum areas of reach for left and right arms. Broken lines indicate the enclosed area covered by the hands when the forearm is pivoted on the bent elbow. (*b*) Area inside which small objects are most easily picked up. (*c*) Area in which the eye can follow both hands working simultaneously and symmetrically.

ASSEMBLY AUTOMATION

Introduction to Assembly Automation

Computer-controlled machine tools now make complex machined parts; electronic components are installed automatically in circuit boards; machines inspect detail parts on a 100 percent basis; and parts are positioned, assembled, and checked out automatically in the creation of assemblies—untouched by human hands. Robots of all descriptions have become part of the industrial scene.

It is true that most businesses automate primarily to reduce costs and, thereby, improve their competitive position in the market. However, the real objective of this investment is to make money, not just save money. When compared with manual assembly operations, the benefits usually derived from automated assembly include:

- Reduced unit costs
- Consistent high quality
- Elimination of hazardous manual operations
- Increased production standby capacity

Semiautomated operations are those in which the worker plays a substantial role in the activity. The worker's role exceeds that of supplying the automated equipment with parts or materials, or removing finished parts from the work area. To date, the preponderance of factory operations has actually been semiautomated rather than fully automated, because the worker-machine combination is often the most efficient and effective in involved tasks.

Basic Automation Concepts

One key rule is that part design must be compatible with the needs of automatic feeding. Parts are usually introduced to an assembly machine as bulk components. They are placed in a hopper and tracked to a loading station. Whether the hopper is vibratory, rotary, or oscillatory, it relies on gravity and/or friction for part movement. Some sort of gating or orientation device allows only those parts in the proper attitude or position to enter the track.

The main part, or body, that will receive the oriented parts must be strong enough to withstand assembly tooling forces. Typically, forces for assembly are not as high as for machining, but pressing, sizing, or machining operations might be required on the assembly machine. High production rates may increase these forces.

The main part must be placed accurately on the assembly machine. This calls for fixturing, flat-locating surfaces, precision-locating holes, and so on. Parts are most efficiently placed in the main body with simple, short, straight-line movement. Grasping a part may be necessary. This requires some type of actuating force with its attendant timing and control elements. If spearing or grasping the part is impractical, a vacuum force may be used in transferring parts. Magnetic force is used occasionally in handling parts, but this is not recommended, because the attraction of metal chips and dirt degrades equipment performance rapidly. Also, residual magnetism often cannot be tolerated in the final assembly. The author experienced problems with the Dragon rocket motor assembly machine due to the cast retainers occasionally becoming magnetized due to improper heat treatment of the stainless steel. We had to degauss them all to achieve good hopper feed.

Types of Automated Assembly Machines

Standard Machine Bases. There are essentially four types of standard base assembly machines:

1. Dial indexing machines
2. In-line machines
3. Floating work platform machines
4. Continuous motion machines

To meet specific assembly automation needs, we add custom tooling. For maximum cost-effectiveness, we can choose from a stock of standard operating stations such as those for feeding, orienting, inspecting, and acceptance/rejection testing. Standard base machines and operating stations are outgrowths of the industry's experience in designing, building, and using machines for high-volume production programs.

Dial Indexing Machines. The dial indexing automated assembly machines incorporate a mechanical drive that rotates a circular dial table, or baseplate, and indexes with a positive cam action. A circular, nonrotating table simultaneously raises and lowers a reciprocating upper tooling plate, usually mounted in the center of the larger rotating baseplate. Assembly nests are installed around the outer edge of the dial table. Parts feeding, assembly, and inspection stations are installed around or above the assembly nests or on the upper tooling plate.

These machines offer the following advantages:

- Greater machine accessibility and minimum floor space. The basic circular layout of dial-type machines is inherently more compact. High machine accessibility increases operator efficiency and simplifies maintenance.
- Greater adaptability to a variety of operations. The dial types of automated assembly machines, containing central indexing mechanisms and reciprocating tooling plates, offer simplified rotary and up-and-down tooling motions for high adaptability to many automated assembly operations.

Figure 14.4.8 shows an elementary rotary indexing machine. The dial type previously described has the added feature of a reciprocating tool table mounted above the indexing table.

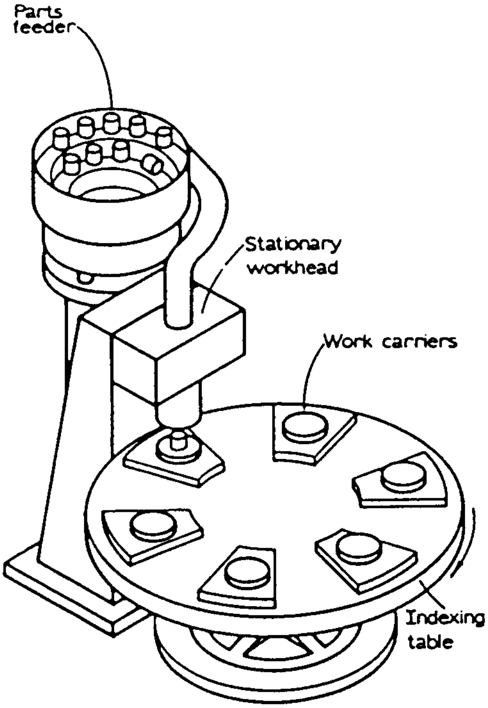


FIGURE 14.4.8 Rotary indexing machine. (*From Geoffery Boothroyd,* Assembly Automation and Product Design, *Marcel Dekker, New York, 1992.*)

In-Line Assembly Machines. In-line automated assembly machines feature a rectangular chassis housing an indexing mechanism driving an endless transfer chain. Nests that hold and transport the product during the various assembly operations are fastened to the transfer mechanism. The parts feeders, workstations, and inspection stations are then arranged along the work flow. Parts are fed into the assembly nests as required, and work and inspection operations are performed in sequence along the length of the machine until the product is completed.

These machines have the following advantages:

- Unlimited number of workstations.
- Efficient operator loading. The rectangular configurations permit machines to be placed side-by-side with an aisle in between. The operator can efficiently monitor all stations from the central aisle.
- Work can be performed from two or three directions simultaneously.

Figure 14.4.9 shows an in-line indexing machine.

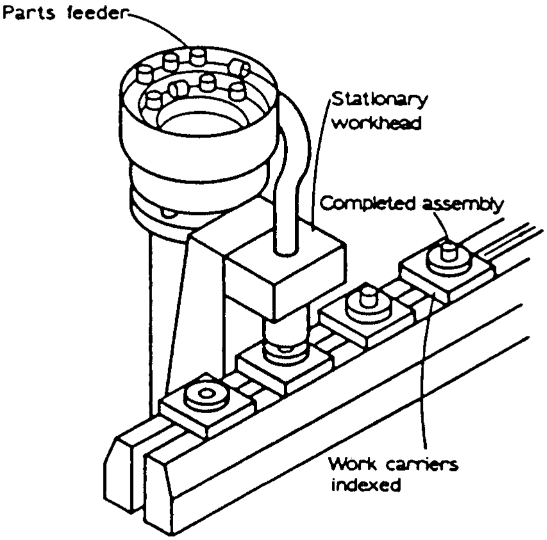


FIGURE 14.4.9 In-line indexing machine. (*From Geoffery Boothroyd,* Assembly Automation and Product Design, *Marcel Dekker, New York, 1992.*)

Floating Work Platform Machines. In floating work platform machines, parts flow into a manifold where they are located, assembled, and inspected. This system uses divergent flow channels for tandem and/or parallel operations to achieve line balancing and consists of two major elements: a parts-transporting element and a modular assembly element.

The parts-transporting element moves the floating work platforms sequentially to the various modular assembly elements. Each modular assembly element consists of an independently powered unit containing one or more workstations. Use of a simple transporting band permits flexibility within the system. Modular assembly elements can be placed in remote areas such as cubicles, barricaded hazard rooms, holding or curing rooms, or storage banks and can be returned to the main system by the parts transportation element for further processing.

Continuous-band motion also permits the routing of parts onto a constant-motion machine for nonstop performance, as well as for routing to in-line or dial-type machines.

The quality of each assembly may be verified by inspection probes placed in tandem following the work performance at each of the workstations. Stations may be used for assembly function testing.

This type of machine has the following advantages:

- Banks of parts may be accumulated between the workstations to cope with short station stoppages.
- Work can be removed from the system, performed at a hand station, and returned to the machine.

Continuous-Motion Machines. Continuous-motion automated assembly machines provide for nonstop performance of operations. Such systems may be capable of up to 1200 assembly operations per minute. Parts are swept from a conveyor belt, oriented, and fed into the machine. Following assembly, inspection, and function testing, the assemblies are oriented and returned to the conveyor belt.

This type of machine has the advantage of higher production rates that can be achieved with other types of bases. The free-transfer machine shown in Fig. 14.4.10 shows a buffer position between the two workheads. The buffer parts could be shuttled off-line to another work position, and then back to the main feed line, in either system.

In general, the higher the production rate, the lower the per-unit cost of a product. Assembly automation systems are designed to fit production rates to specific needs. Good machine design considers more than the production rate; it also considers the overall production capa-

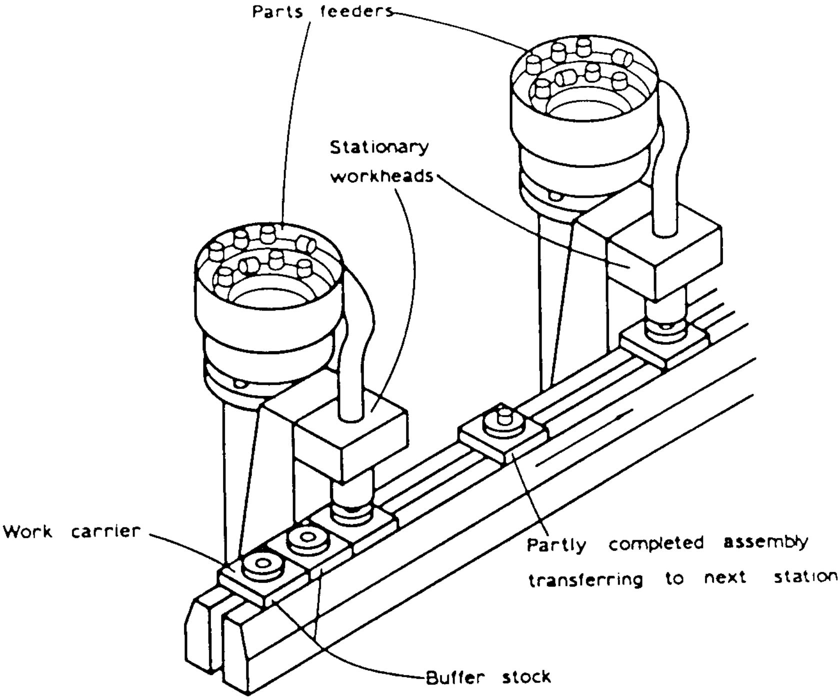


FIGURE 14.4.10 In-line free-transfer machine. (*From Geoffery Boothroyd,* Assembly Automation and Product Design, *Marcel Dekker, New York, 1992.*)

bility, including such factors as minimum maintenance, system efficiency over years of continuous operation, minimum training required for operators, and production of a consistently high-quality product. Flexibility is important in every assembly automation system. Modularized workstations, idle stations, and standardized motions make systems adaptable to product changes with minimum downtime.

Robotics

A *robot* can be broadly defined as a machine that copies the function of a human being in one respect or another. Generally, industrial robots are equipment with a single arm, and they are used to perform assembly-line operations and other repetitive tasks such as feeding parts into another machine.

The assembly machines we described in the previous paragraphs are designed to handle large numbers of standard workpieces. These devices could be regarded as the forerunners of the modern industrial robot, although, unlike most robots, they are controlled by the machine to which they are attached and may not be readily used to perform another function. The cost of reconfiguring the grippers or end effectors plus the reprogramming cost may make the robot less flexible in assignment than is sometimes imagined.

The real differences may be in the "eye of the beholder"—or in the mind of the reporter or author. The term *robot* comes from the Czech word *robota,* meaning work, and was first used in a play called *R.U.R.* (standing for "Rossum's Universal Robots"), written in 1920 by the Czech author Karel Čapek. I personally find the term *robot* to be rather imprecise, and one that should normally be replaced by a more descriptive term. Perhaps the best definition is by example. A robot consists of three basic assemblies:

1. Motion system
2. Control system
3. Heads and work tools

Motion Systems. The motion systems start with the basic two-axis linear-rotary models as sketched in Figure 14.4.11. These high-speed, servo-controlled robot systems are designed for a variety of material handling and pick-and-place operations. The robot consists of a high-speed linear table, rotational table, arm, and work tool to provide high-speed positioning over a large work area. An optional Z-axis could be added (between the arm and θ-axis) to permit raising or lowering parts from one height to another.

Providing three axes of motion (X, Y, Z), the robots shown in Fig. 14.4.12 can perform various functions within a large volume. High positional accuracy of the X-Y-Z tables makes this

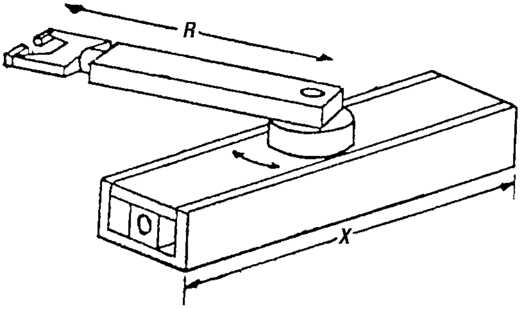


FIGURE 14.4.11 Two-axis motion system (X, R).

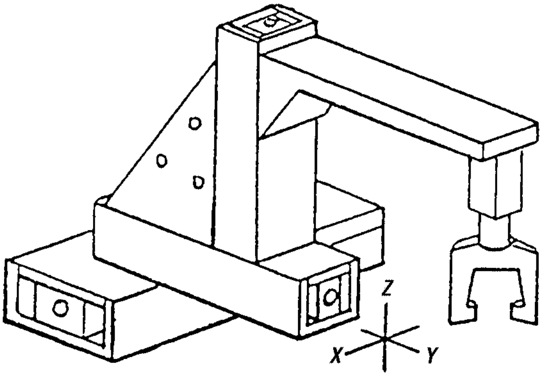


FIGURE 14.4.12 Three-axis motion system (X, Y, Z).

robot ideally suited for intricate tasks, such as stuffing components onto PC boards. The *Z*-axis capability permits components to be selected and positioned at various vertical levels.

The basic *X*-*Y*-*Z* rotary model is shown in Fig. 14.4.13. These robots, featuring *X*-*Y*-*Z*-θ motion plus a special work turret, offer exceptional versatility for robotic applications. The *X*-*Y*-*Z*-θ motion permits work to be performed on a three-dimensional workpiece from the top as well as two sides. The turret may contain an electro-optical sensor for position location and autocentering. For performing multiple tasks, other turret positions may include a variety of tools, such as a screwdriver, Allen wrench, and grippers.

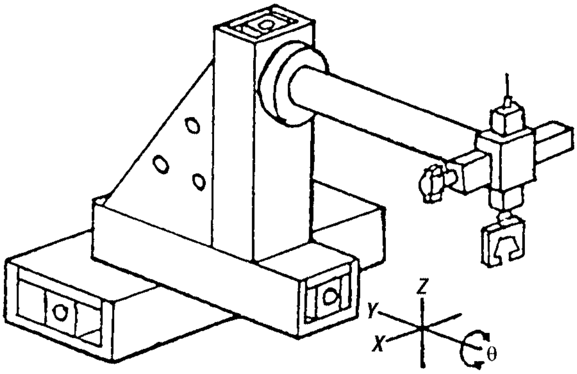


FIGURE 14.4.13 Four-axis motion system (X, Y, Z, θ).

Extended work area robots, featuring five axes of motion ($X, Y, Z, \theta_1, \theta_2$), provide ultimate flexibility in servicing a 360° area around the robot in a large volume. When employing the same turret as the four-axis models, these robots can be programmed to provide a single robot assembly station with multiple-task capability. The robot may also be placed to service an assembly line on either side of it. See Fig. 14.4.14 for a schematic.

Robots (and assembly machines) today are normally designed by assembling standard components and assemblies to fit specific needs. The *X*-*Y* tables can position parts to ±0.025 mm (±0.001 in), at speeds as low as 0.0254 mm/s (0.001 in/s) or as high as 1524 mm/s (60 in/s) with accelerations to 4*g*.

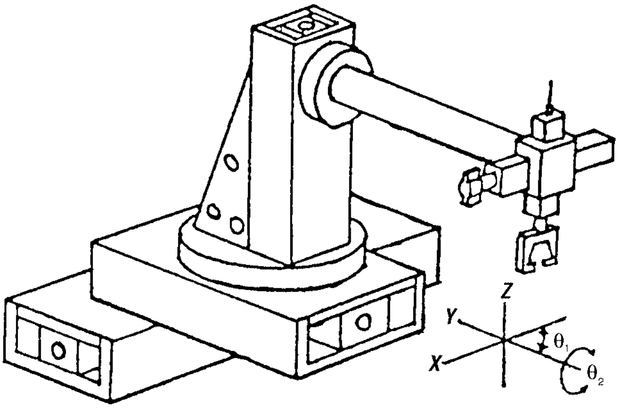


FIGURE 14.4.14 Five-axis motion system (X, Y, Z, θ_1, θ_2).

Control Systems. The controls may be a programmable positioning controller consisting of a microprocessor-based CNC system with built-in hardware calculators. This permits simple manual programming via a keyboard. Program entry may also be from floppy disk or direct from a central or local area network (LAN) computer. Simultaneous interpolation up to six axes linear and three axes circular are becoming standard. The controller will accept positional feedback from optical encoders, interferometers, inductsyns, and resolvers. Transducer outputs, such as pressure, torque, and power levels, may also be input. Other input/output functions available are usable in tuning operations, such as tuning a coil to its peak, or adjusting a potentiometer to a desired output level. Here, the work tool motion is controlled by a feedback signal to perform the adjustment to the desired device output signal. Most robots today also have a teach pendant, which can be moved manually through the desired positions to program the controller or computer. The program generated by a teach pendant can then be printed out, and minor reprogramming steps can be added to smooth the motions.

Figure 14.4.15 shows an unmanned robotic cell in a flexible manufacturing system, built around robots that handle parts and material, perform assembly tasks, operate tools, and perform other manufacturing operations. This cell is built around a Cincinnati Milicron T^3 material-handling robot. The robot controller, the material-handling system and its controller, the fine-resolution system and its controller, and the automatic riveter and its controller receive signals through a multiplexer from a central computer.

In designing a robotic system for manufacturing, the flexible system concept just described should be the base on which the largely unmanned robotic system should be built. Figure 14.4.16 shows the floor layout for an application developed by the National Institute of Standards and Technology in Gaithersburg, Maryland. A deburring cell has been developed that demonstrates the deburring of parts based on their description and a graphically developed process plan. This cell, a cleaning and deburring workstation, consists of a workstation controller, two robots, various quick-change deburring tools, a rotary vise for part fixturing, and a part transfer station.

Heads and Work Tools. The working head may include a turret, similar to a lathe. The variety of mechanical grippers, vacuum grippers, screwdrivers, nut runners, and the like, is almost endless. The type most similar to a human hand, with multiple linkages and force-feedback servos, is often pictured in the press as standard, but, in fact, it is very expensive and more commonly seen as a laboratory experiment than a factory working tool.

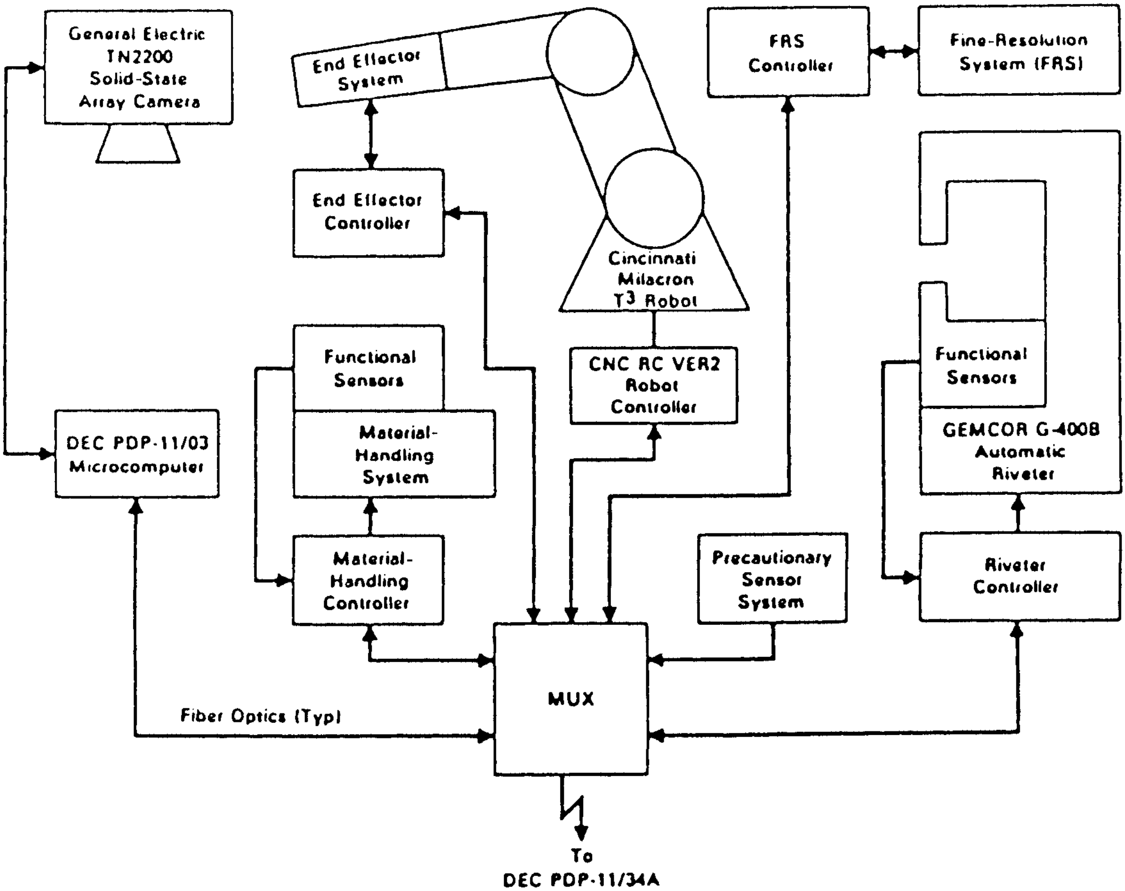

General Electric TN2200 Solid-State Array Camera
End Effector System
End Effector Controller
Cincinnati Milacron T3 Robot
FRS Controller
Fine-Resolution System (FRS)
Functional Sensors
Material-Handling System
Material-Handling Controller
CNC RC VER2 Robot Controller
DEC PDP-11/03 Microcomputer
Functional Sensors
GEMCOR G-400B Automatic Riveter
Precautionary Sensor System
Riveter Controller
MUX
Fiber Optics (Typ)
To DEC PDP-11/34A

FIGURE 14.4.15 Manufacturing cell schematic. *(Courtesy McDonnell Douglas Corp.)*

ELECTRONICS ASSEMBLY

Introduction

Electronic assemblies consist of any number of electronic and nonelectronic devices (e.g., screws, heat sinks, carrier plates, etc.) grouped together to perform a function. Each assembly is a self-contained production item that follows its own process flow. For example, an insertion-mounted printed wiring board (PWB) can be built in the same facility as a surface-mounted PWB; however, different equipment and processes are used. Both boards will be populated by different pick-and-place or insertion machines. A wave solder system is commonly used for insertion boards, while surface-mount boards use solder paste or thick solder plate reflowed in a vapor-phase or infrared (IR) furnace.

System Integration

Components, such as bare dies and capacitors, are the building blocks of many electronic assemblies. Subassemblies, including these components, chip carriers, PGAs, and hybrid

MANUAL AND AUTOMATED ASSEMBLY

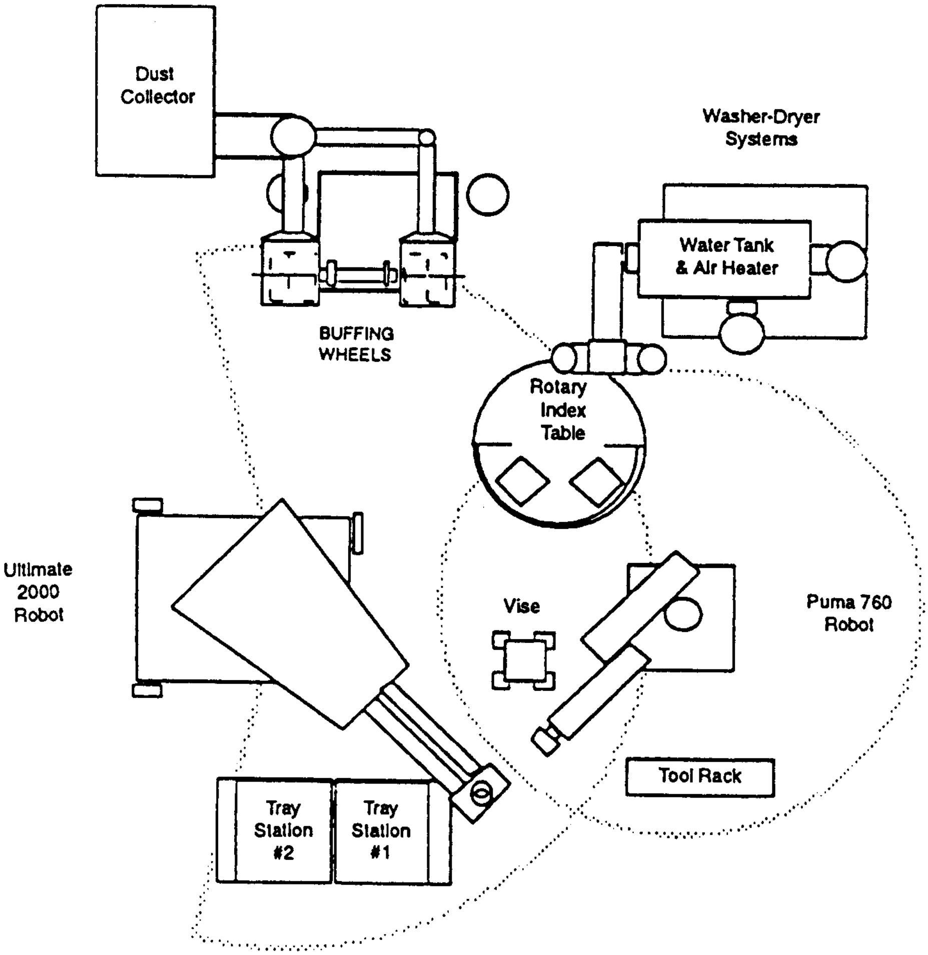

Dust Collector
Washer-Dryer Systems
Water Tank & Air Heater
BUFFING WHEELS
Rotary Index Table
Ultimate 2000 Robot
Vise
Puma 760 Robot
Tool Rack
Tray Station #2
Tray Station #1

FIGURE 14.4.16 Cleaning and deburring workstation utilizing robots. *(Courtesy U.S. Department of Commerce.)*

assemblies, are the building blocks of PWB assemblies. In turn, PWBs are the building blocks for final systems.

A typical packaging hierarchy of an electronic system is shown in Fig. 14.4.17. The lowest level of packaging, or the *zeroth level,* is generally considered to be the semiconductor chip, although discrete passive devices such as resistors and capacitors may also be included. The packaging of a chip or a set of chips in a functional and protective chip carrier is referred to as the *first level* of packaging. Chip carriers can range from single-chip (monolithic) carriers to very sophisticated multichip modules containing hundreds of chips and devices. The *second level* of packaging is often referred to as the electrical circuit assembly (ECA). At this level, the individual chip carriers are mounted on a common base, usually a PWB. The *third level* of packaging typically involves the interconnection of circuit boards and power supplies to a physical interface, such as a chassis, control, and/or electromechanical device or system. The third level of packaging may also involve the connection of several boards within a supporting or protective structure such as a cabinet. Several such cabinets are joined together to form the *fourth-level* of packaging.

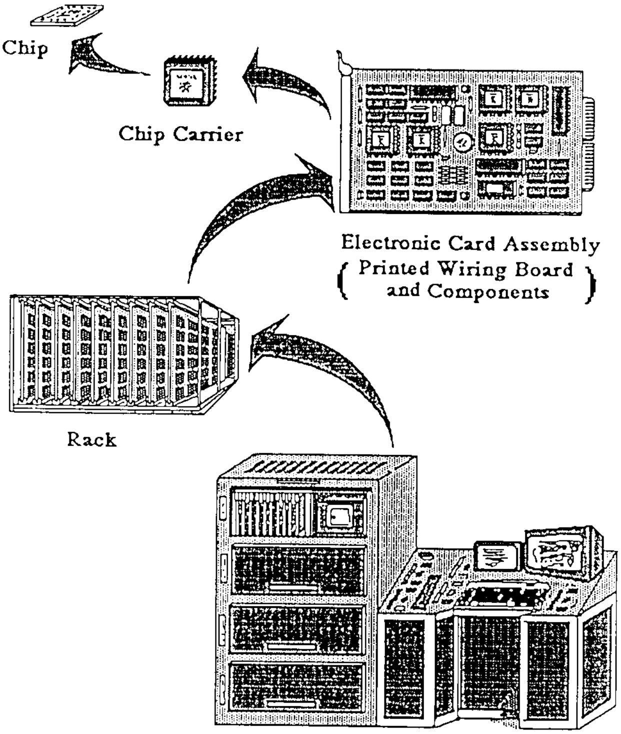


FIGURE 14.4.17 Packaging hierarchy of an electronic assembly system.

Organic PWB Assemblies

Organic boards are composite structures. For example, in epoxy glass boards, glass fibers are suspended in an epoxy resin. Polyamide boards are composed of glass fabric, with polyamide as the dielectric material. These are the most common industry combinations. The individual layers of organic boards are metallized with copper, have patterns etched on them, and then are laminated together. Interconnection between the layers is accomplished with *through-holes,* blind vias, or buried vias. The method of intralayer connection and the design of the mounting pads determine the type of assembly used. If only insertion-mounted components are used, then all connections from the components to the board are through-holes; the mounting pads are actually holes in the board. Routing signals from one component to another can be accomplished by through-hole, blind via, or buried via. Because the assembled board will have holes with leads extending through them, insertion boards typically do not have components mounted on both sides. Any components mounted on the bottom of the board are typically small, hermetic chip components, mounted with epoxy to hold them in place as they travel through the solder wave.

Boards routed with buried vias have limited reworkability and lower yields, but they offer increased surface-mounting area and fewer routing layers. These surface-mount designs can also be routed to allow double-sided mounting. Surface-mount boards must be laid out to include mounting pads of the right size, component tolerances, and proper solder fillets. These boards often have both leadless and leaded components; the latter require surface-mount lead forming.

Electrical parameters must also be taken into account during board layout. Components with a high-voltage potential between them should be separated to prevent arcing. When an arc occurs, the voltage travels across the board material and can burn a trail, or carbon track, in the polymer on the board surface. If the arcing itself does not short out the circuit or damage the components, the carbon track left behind can cause shorts later on. Carbon tracking can be avoided by putting additional space between all tracks and components, but size limitations usually preclude this solution. The more common prevention method is to give the board assemblies a protective overcoat that reduces the available surface path for the voltage.

Boards can also be designed to accommodate both inserted and surface-mounted components together. The layout of mixed-technology boards greatly influences the assembly processing. If all inserted components are mounted on one side, low-profile, hermetic, surface-mounted chip components can be tacked down, or epoxied, to the bottom side and reflow can be accomplished with wave solder. Therefore, mixed-technology processing is similar to that for insertion mounting. If inserted and surface-mounted components are placed on the same side, the processing is similar to surface mounting. See Fig. 14.4.18.

Heat Sink Attachment

For low-power commercial applications, components are mounted directly on the PWB. For high-power or military applications, the first step in the assembly process is to attach the PWB to a heat sink or carrier plate. With an insertion-mounted board, the carrier is either an edge support or a thermal ladder. The edge support, which can be attached to the bottom or top of the PWB or wrapped around its sides, braces the edge of the PWB, leaving the center free for device placement. A thermal ladder is a heat sink attached to the top of the PWB with windows or slots cut in it; the component [i.e., a plastic dual in-line package (DIP), ceramic DIP, or cerpak] straddles the ladder and the leads go through the slots into the PWB, as shown in Fig. 14.4.19. This design provides a thermal path directly from the ceramic component to the heat sink, rather than through the leads.

Surface-mount boards typically use some edge supports, whether leadless or with a configuration that permits both leads and package body to be mounted on the plane of the board. Straddling a thermal ladder is difficult with these designs.

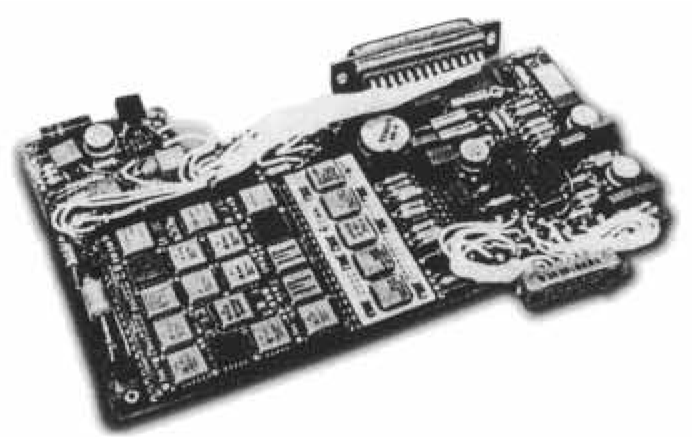


FIGURE 14.4.18 Insertion mount motherboard assembly with two connectors, jumper wires, one ceramic daughterboard assembly, one organic surface-mount assembly, and discrete insertion-mount components. *(Courtesy of Westinghouse Electronics Systems Group.)*

Heat sinks can also be attached to the bottom using a B-stage epoxy for organic surface-mount PWBs. The PWB, epoxy film, and carrier plate are cured together under controlled pressure and temperature. In some cases, the PWB assembly is double-sided, sandwiching two boards over the heat sink; this cored board doubles the surface-mountable area with a minimal increase in board assembly height or volume. Although this design forces a thermal path through the PWB, the components are in contact with the surface and assist with primary cooling, as depicted in Fig. 14.4.19. Thermal management of this design is enhanced by placing

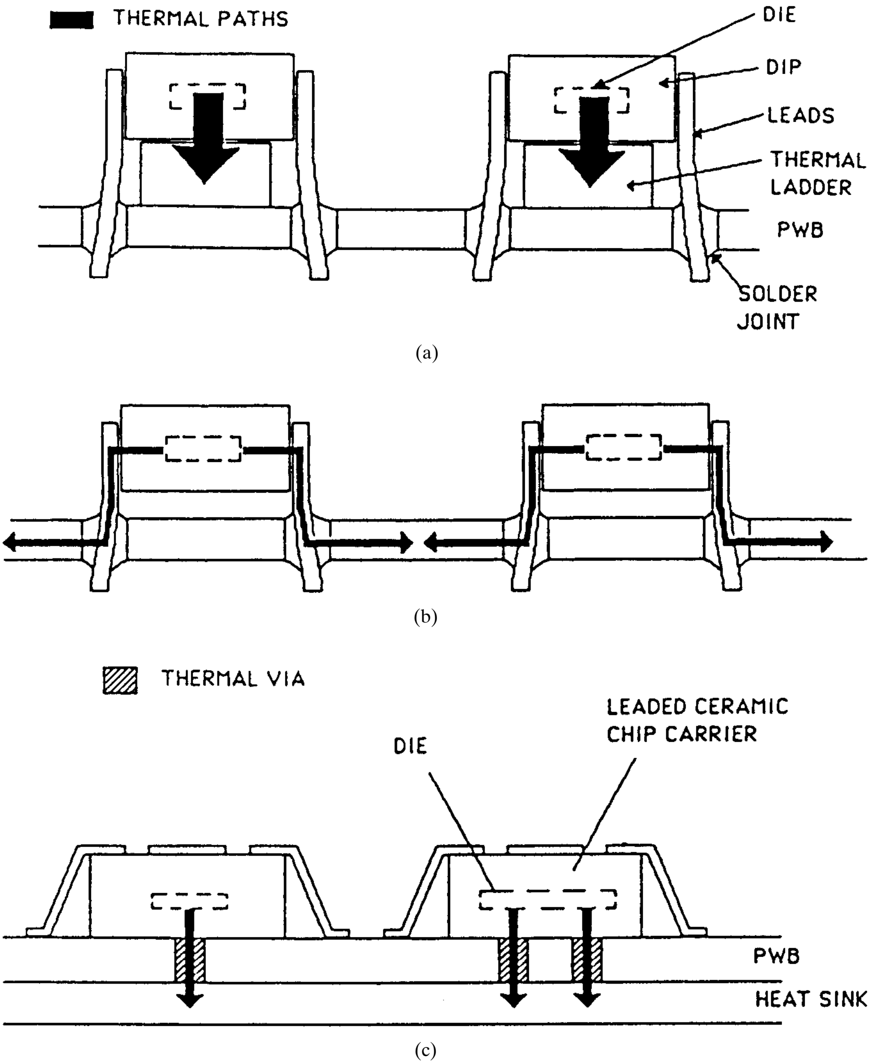


FIGURE 14.4.19 Thermal paths. (*a*) Insertion-mounted organic PWB with thermal ladder. Heat is dissipated from the die through the DIP floor to the heat sink. (*b*) Insertion-mounted organic PWB. Because the DIP stands off the PWB, the heat must be transferred from the die, through the DIP, through the leads, through the solder, to the PWB, out to an edge support heat sink. (*c*) Leaded surface-mounted organic PWB with cavity-up chip carriers.

vias under the packages, which are not only used for routing, but also act as thermal vias, to provide a more efficient and direct path from component to heat sink.

Heat sink or core materials offer improved thermal conductivity over the PWB material. These materials include aluminum, Kovar, copper-clad Invar, copper-clad nickel, graphite composites, copper-clad molybdenum, and metal-matrix composites, such as silicon-aluminum materials.

Most heat sinks can be attached with epoxy films, usually thermally conductive B-stage or prepreg sheets, or with other film adhesives. Material and adhesive choices depend on the requirements of the system or PWB assembly. If cost and weight are more critical than thermal management—that is, if the assembly will not be subjected to severe or rapid temperature changes—aluminum attached with standard B-stage is appropriate. If thermal management or power dissipation is critical but there are no restrictions on weight or outgassing, then copper-clad Invar attached with a flexible silicon adhesive to absorb the CTE mismatch might be preferred. If thermal management and weight are both critical, the answer might be a graphite heat sink with silicone adhesive.

Insertion Mounting of Components

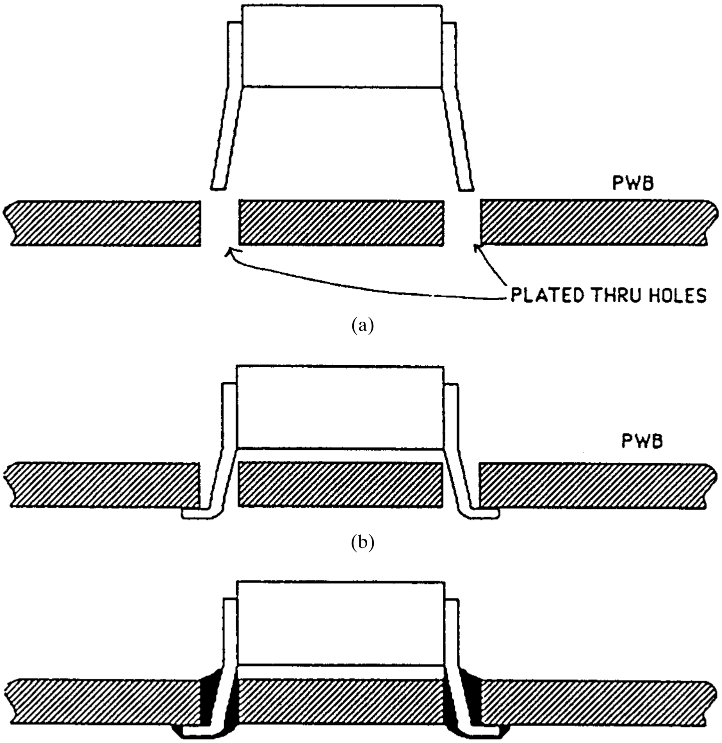
On an insertion-mounted board, all components and subassemblies must be leaded, and the leads must be configured or mechanically formed for insertion into the mounting holes of the board. On pin-grid arrays, the leads are already in the correct configuration for insertion, perpendicular to the bottom of the package. Dual in-line packages are also designed for insertion, with the leads along the side of the package, pointing down. The military standard configuration specifies leads at a 6° angle from perpendicular.

Components such as resistors and capacitors are leaded round cylinders, with leads formed into a right angle for insertion by pick-and-place equipment. This machine sends a robotic arm to the bin, tape, or feeder to select the component, picks it up by vacuum or tweezer grabbing, transports it to the lead former, where it is pushed into a troughlike fixture that bends the leads as they are forced against its sidewalls. Lead forming can also be done by two robotic arms that grab the leads and turn to bend them appropriately. The holding arm then carries the lead-formed part to the board, where it inserts or mounts it in a preprogrammed location. This is done within tight tolerances and within seconds. The DIPs are normally supplied in tubes or feeders for the placement equipment, with leads already formed. Chip carriers and hybrids normally have preformed leads created by arms that grab the leads and force them into the necessary L-shape while the package is tightly cradled. After the components have been inserted, automatic lead trimmers cut and flatten the leads coming out of the bottom of the board. See Fig. 14.4.20.

To prepare the boards for component placement, the PWB is plated with a tin flash that protects the copper metallization against corrosion, or a thick plate of solder. Once all the components are inserted, the board is sent on a belt that pulls it across a wave of flux foam and then a wave or waterfall of liquid solder. The bottom of the board floats over these waves. The flux, activated by temperature, deposits flux over the entire board, removes oxides on the surfaces to be soldered, and allows solder to wet these surfaces and wick up the leads and into the holes, forming the solder joints. Usually, components are mounted only on the top side of the board; components mounted on the bottom must be small enough to ride in the waves without compromising surface contact, and they must be attached to the bottom with an epoxy so they will not fall off before the solder fillet interconnections are formed. After soldering, the boards are cleaned and inspected prior to final electrical testing.

Surface Mounting of Components

Surface-mount components can be either leaded or leadless, such as chip capacitors, chip resistors, or LCCs. Surface-mount organic boards can be routed with any combination of



(a)

(b)

(c)

FIGURE 14.4.20 Insertion mounting and lead trimming. (*a*) Component and board. (*b*) Component inserted in a board with leads cut and clenched. (*c*) After wave solder.

through-holes, blind vias, or buried vias; PWBs can have heat sinks attached directly to the back side of the board, because there is no need to leave this area clear for lead protrusions.

The advantages of surface-mount technology over insertion mounting are reductions in routing layers, in the assembly's profile, and in board area. Components can be mounted on pads on the board's surface, obviating the need for through-holes for component mounting. In addition, board routing can be accomplished with blind or buried vias, which also eliminate the need for through-holes and extra layering to allow for routing around the holes.

Surface-mount components usually sit lower than their inserted counterparts and sit directly on the board surface, not slightly above, as shown in Fig. 14.4.19.

With system trends toward increased complexity, decreased size, and cost-effectiveness, surface-mount designs offer great reductions in height, area, and system volume and cost no more than inserted components.

The price of leadless components is also comparable with or less than that of their leaded counterparts. A leaded chip carrier is slightly more expensive than the leadless version, because it requires brazing the leads onto the leadless version; leadless components also allow larger placement tolerancing due to their ability to self-align.

CONCLUSIONS AND FUTURE TRENDS

The role of the industrial engineer, manufacturing engineer, process engineer, tool engineer—by whatever name has evolved over the years—will continue to play an even more important role in the design and production of future products. The line between product design and production operations will continue to fade. We see many cases today where the old order of development of new products is reversed. This now starts with the customer, moves to the production departments, and is committed to firm drawings as the final step. This trend will continue.

Mergers and acquisitions have created some very large manufacturing companies. There is another exciting story developing in parallel with this trend. Many small existing companies, as well as new start-up companies, have made a name for themselves by the adoption of new processes in the assembly area. Today, a small company with less than 50 employees may spend millions of dollars in the acquisition of automated assembly equipment—in addition to advanced fabrication machines. The industrial engineer may act as the person charged with equipment design, construction, supplier selection, purchasing, estimating—and the management and supervision of operations. Establishing the assembly processes, whether they are manual or highly automated, becomes the major driver in product design. This is true when the product is primarily in the electrical or electronic arena, or is based on mechanical assembly—because all assembly is composed of mechanical work.

Our global economy has forced manufacturers to shorten the time between customer demand and delivery, improve first-time quality, and produce at a cost that is truly competitive in the world marketplace. Total real-time cooperation between all players and disciplines must continue to accelerate at a rapid pace.

The very large companies working in small focused groups, and the very small companies working in even smaller groups, require engineers (by whatever name) to become competent in many fields! Understanding product requirements from the customer's point of view on one hand, and the ultimate production of the finished goods on the other—offers an exciting challenge for the future.

FURTHER READING

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BIOGRAPHY

Jack M. Walker, who is presently active as a consultant in design and production areas, has held the following positions: Director of Factory Operations (Ret.) for McDonnell Douglas high-rate missile programs, involved in all elements of production and production support. Resident manager of European coproduction programs, working with Swiss and Dutch industry. Branch manager of Production Design Engineering—also wrote *Production Design Manual* and *Introduction to Composites.* Editor of *Handbook of Manufacturing Engineering* for Marcel Dekker, New York—wrote several chapters in handbook. Senior member of SME, Professional Member of AIAA, and member of ASM. Industry member of University of Florida Engineering Advisory Council. Executive Director of Brevard County (Florida) Manufacturer's Association.

CHAPTER 14.5
FLEXIBLE AUTOMATION

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In the past, the mainstream of manufacturing was mass production, which lends itself to automation. More recently, consumer demands have made multiproduct, small-lot size production more and more common. This in turn requires a new style of automation, often called *Flexible Automation* or FA. Compared to the automation of individual process steps, automation of whole production systems is much more difficult and introduces new requirements. The reasons companies pursue automation are changing, and a major impetus today is to achieve a more comfortable working place for employees. Another trend in automation today is the growing importance of integrating it into the companywide information system.

Automation cannot be considered in isolation. To get full benefit, product designs must be reviewed and changed to facilitate automation. This chapter provides a systematic approach to reviewing production processes, including human-machine relationships, to optimize the application of automation. Specific manufacturing process steps are examined as to their suitability for automation.

INTRODUCTION

The word *automation* was used in 1948 at the Ford Motor Company in the United States, in the context of a program for enhancing efficiency in the company's factories. At Ford, in those days, *automation* referred to a production system which the company had adopted, based on the use of conveyer systems and transfer machines. There, in the case of part fabrication, for example, the feeding of parts, the order of operations of cutting tools, and the settings for each operation could all be set in advance and executed mechanically, by means of built-in cams and so forth. This was automation in a mass production environment.

In the late 1950s, with increased diversification of products, more flexible production lines were required. In Japan, people began to study Toyota's production system, and from that work, the Kanban System, "mixed flow lines," and "single setup" (setup changes taking less than 10 minutes) were developed. At about the same time numerical control (NC) machine tools, which had already been used in the aerospace industry, began to be adopted by industry in general.

Then, in the early 1980s, the use of industrial robots and unmanned vehicles spread, and FMS *Flexible Manufacturing Systems* (FMS) and *Flexible Automation* (FA) became major topics. In most FMS applications, multistation, in-line indexing transfer machines are used. However, increasingly, *Computerized Numerical Controlled* (CNC) machines, sequencers, and so forth are being utilized, and in such cases, the term *Programmable Automation* (PA) has come into use.

In Flexible Manufacturing Systems, the *building block* method is sometimes adopted. In this method, standard modules such as transfer units, handling units, heads, and index-tables which were designed beforehand, are combined to form production systems or lines.

Recently, since the variety of product models is increasing and product life cycles are becoming shorter, the need for Flexible Automation has increased even more. As the number of product models increases, the lot size for each kind becomes smaller, while the number of setup changes increases. Similarly, if shorter lead times are required, the trend toward small lots will be even stronger. In short, automation is required today not only for mass production situations but also for multiproduct, small-lot production systems. In general there is a trend toward creating production systems that use fewer operators. Therefore, in this chapter we will describe a way of analyzing manufacturing situations and designing and implementing the automation of multiproduct, small-lot production systems.

AUTOMATION AND THE ROLE OF THE INDUSTRIAL ENGINEER

Automation of whole production systems is different from the mechanization or automation of single process steps. It is also different from mere automation of a fabrication area or assembly process. For the automation of an entire system, each individual operation or process step must first be automated (i.e., from the fabrication/stocking/supply of parts and materials, through the steps of assembly, adjustment/testing, and packaging, to warehousing, including the management thereof, and shipping). In addition, automation of the product flow system, which moves work from one processing station to the next, is necessary. However, in the present situation, companies still have not achieved a level of automation that functions as an integrated system with all elements well coordinated. To achieve such a level of automation, which takes the entire production system into consideration, it is necessary first to review product designs, apply standardization, study and perhaps adopt new processing methods, improve processes, review layouts and material handling schemes, and extend the application of tools, fixtures, and jigs. These are areas where industrial engineers should take an active part, and through improvements in these areas, good results can be anticipated with only small investments. Figure 14.5.1 shows the respective areas of responsibility for mechanical engineers (facilities design, etc.) and industrial engineers. In essence, automation of single process steps is mainly the job of mechanical engineers, while automation of the whole production system is the task of industrial engineers.

Mechanical engineering	Industrial engineering
Automation of equipment	Automation of production systems
Design of equipment	Design of production systems
	Application of new equipment
Design of molds, dies, tools, and jigs	Specification of tools, fixtures, and jigs
Investigation of new equipment (cutting tools, etc.)	Introduction of new cutting tools, etc.

FIGURE 14.5.1 The respective responsibilities of mechanical engineering and industrial engineering.

PROCEDURES FOR MECHANIZATION/AUTOMATION

The automation of single process steps can be completed by mechanical engineers by themselves. However when production systems are totally reevaluated, and large cost reductions attempted, systematic analyses and approaches are essential. The procedure for undertaking the automation of a production system efficiently and effectively and from a systematic standpoint is shown in Fig. 14.5.2. In the following section we will look at the points which must be specifically considered in the automation of production systems according to this procedure.

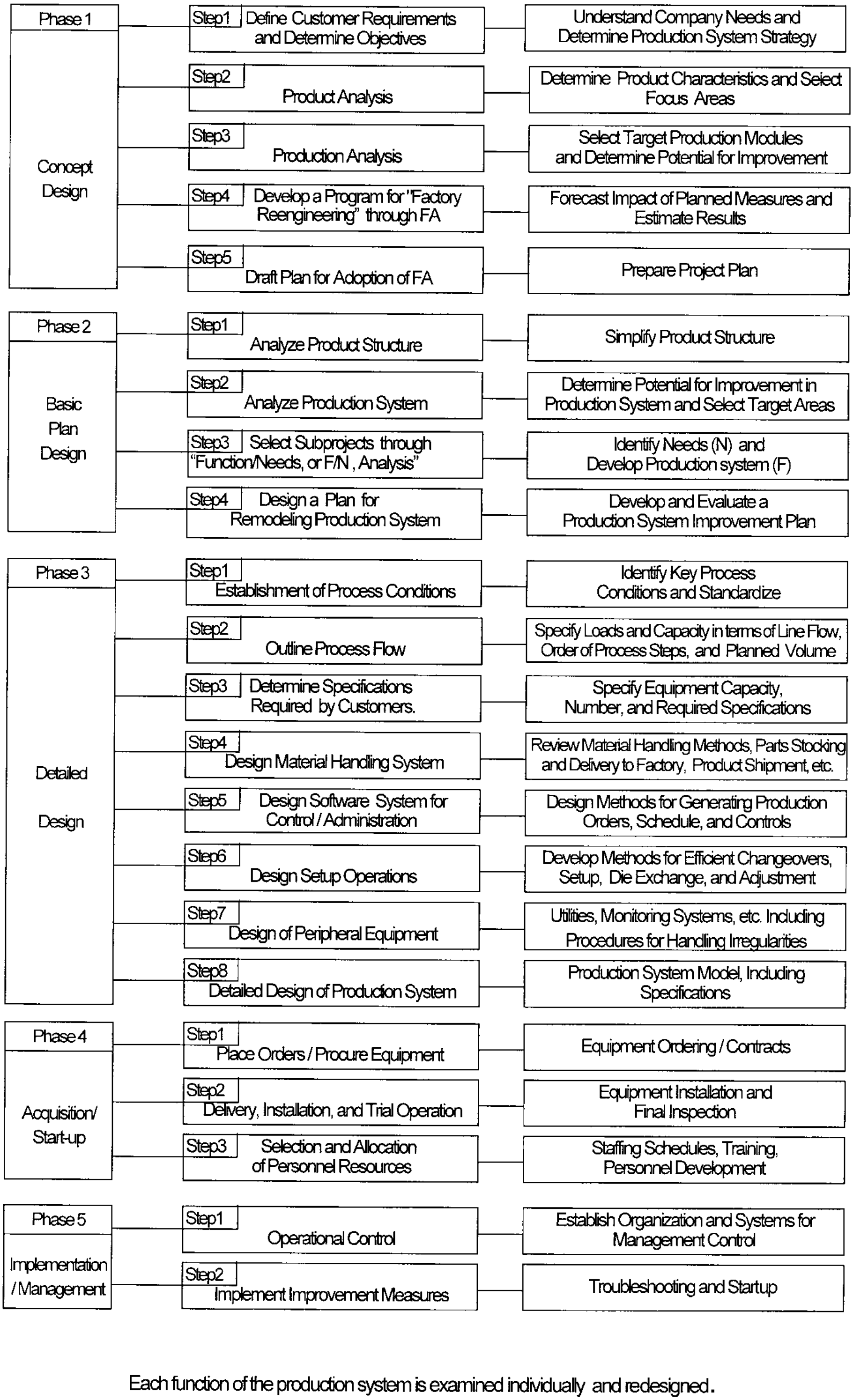
Phase 1
Concept Design
Step1 Define Customer Requirements and Determine Objectives
Understand Company Needs and Determine Production System Strategy
Step2 Product Analysis
Determine Product Characteristics and Select Focus Areas
Step3 Production Analysis
Select Target Production Modules and Determine Potential for Improvement
Step4 Develop a Program for "Factory Reengineering" through FA
Forecast Impact of Planned Measures and Estimate Results
Step5 Draft Plan for Adoption of FA
Prepare Project Plan
Phase 2
Basic Plan Design
Step1 Analyze Product Structure
Simplify Product Structure
Step2 Analyze Production System
Determine Potential for Improvement in Production System and Select Target Areas
Step3 Select Subprojects through "Function/Needs, or F/N, Analysis"
Identify Needs (N) and Develop Production system (F)
Step4 Design a Plan for Remodeling Production System
Develop and Evaluate a Production System Improvement Plan
Phase 3
Detailed Design
Step1 Establishment of Process Conditions
Identify Key Process Conditions and Standardize
Step2 Outline Process Flow
Specify Loads and Capacity in terms of Line Flow, Order of Process Steps, and Planned Volume
Step3 Determine Specifications Required by Customers.
Specify Equipment Capacity, Number, and Required Specifications
Step4 Design Material Handling System
Review Material Handling Methods, Parts Stocking and Delivery to Factory, Product Shipment, etc.
Step5 Design Software System for Control / Administration
Design Methods for Generating Production Orders, Schedule, and Controls
Step6 Design Setup Operations
Develop Methods for Efficient Changeovers, Setup, Die Exchange, and Adjustment
Step7 Design of Peripheral Equipment
Utilities, Monitoring Systems, etc. Including Procedures for Handling Irregularities
Step8 Detailed Design of Production System
Production System Model, Including Specifications
Phase 4
Acquisition/ Start-up
Step1 Place Orders / Procure Equipment
Equipment Ordering / Contracts
Step2 Delivery, Installation, and Trial Operation
Equipment Installation and Final Inspection
Step3 Selection and Allocation of Personnel Resources
Staffing Schedules, Training, Personnel Development
Phase 5
Implementation / Management
Step1 Operational Control
Establish Organization and Systems for Management Control
Step2 Implement Improvement Measures
Troubleshooting and Startup
Each function of the production system is examined individually and redesigned.

FIGURE 14.5.2 Procedure for developing and implementing an FA production system.

MAIN POINTS IN IMPLEMENTING AUTOMATION

Clarifying the Purpose of Automation

The automation of production systems is sometimes necessary because of technical requirements, such as in an operation that can only be performed by a machine process. However, in many cases, automation is adopted for the purpose of cost reduction. In other cases, the economic or labor market situation in the country may make automation desirable. For example, in Japan, during the period of high growth rates, adoption of mechanization/automation progressed because of a shortage of workers and the steep rise in labor costs. More recently, however, the concerns of the industrialized countries have come to focus on subjects like reestablishing human values in the workplace, strengthening competitiveness in the international market, and responding to the diversification of market needs. These priorities in turn encourage more use of automation. For example, the desire to achieve better working conditions for operators (the so-called reestablishment of human values movement), which is in part a response to the trend for young people to exit the manufacturing industry, has caused companies to consider further automation of difficult and "inhumane" operations. Currently receiving consideration for automation are many of the hands-on functions in the construction industry; various operations in foundries and press factories; "dirty" work such as painting, buffing, and sanding; and operations performed under high temperature conditions. The basic philosophy regarding adoption of automation can be summarized in the following objectives, aimed at improving the operator's work environment:

- Freedom from dangerous work
- Freedom from harsh work
- Freedom from simple, boring operations
- Freedom from unhealthy working conditions

When constructing a new production system based on automation, it is necessary first to clarify the direct purpose—what is it that the factory expects to accomplish.

In general, automation can be used to accomplish the following:

- Reduction of operator headcount
- Improvement of working conditions
- Elimination of personal errors
- Improvement of productivity
- Better balancing of cycle times
- Enhancement of nighttime utilization rate

Consequently, the need for automation, the objective to be achieved by it, and the prerequisites for implementation must first be specified. Then, based on these parameters, a plan is mapped out as to the specific type of production line to be built.

Automation and Product Life Cycle

The automation of a production system should be designed and planned to suit the product and production strategy of each specific company. In other words, product types and production volume, and the prospects for those parameters in the future, need to be considered. In this context, a product's life cycle has a major impact on the automation of production systems. In general, from the time the basic competitive viability of a product becomes clear—for example in the case of automobiles, when it became obvious that gasoline engines would be the mainstream—the typical strategy is to turn to automation as the means for achieving cost reduction. Consider the case of watches, for example. Originally, Switzerland was the leading manufacturer, but now Japan has assumed that role. This change occurred because of the emergence of quartz watches. Switzerland also began manufacturing this new type of watch early on, but the Japanese manufacturers (Seiko, in particular) were the ones that moved quickly to implement mass production and automation. Similarly for calculators, Casio and Sharp put them into mass production quickly and were thus able to take control of the industry.

Designating Factory Areas for Implementing FA

In deciding which factory areas are appropriate for implementing FA, the tendency recently has been to consider their relationship to CAD/CAM systems and to the information control system used in the production area. Also, the question of how to relate automation to other information systems, such as *Commerce At Light Speed* (CALS) and *Product Data Management* (PDM) has presently become a topic of great interest. The relationship between these information systems and the targeted areas for application of FA is shown in Fig. 14.5.3.

Establishing the Information Structure of FA Systems

Implementing FA extends beyond mere automation of the production process. Therefore, computerization of the information system of the whole factory is an indispensable element. Information systems can be roughly classified into two groups: (1) the process control systems that control the production system, and (2) the systems that gather, process, and deliver the information ultimately used for control. Systems of the former type were identified at an early stage as appropriate targets for implementing FA, and they have gradually been computerized. More recently, computerization of the latter—namely of CAD/CAM systems, production information control systems, and even CALS and PDM systems—has begun. Figure 14.5.3 depicts the information structure of FA systems. One key to a successful FA implementation is how well the company organically integrates these information systems with the automation system of the factory floor as it specifies, designs, and builds its FA system.

Automation and Product Design

Production systems based on FA assume extensive use of automation, and products must have a structure that enables easy automation of their fabrication and/or assembly. This may require reviewing the product structure and making improvements from the design standpoint. Such improvements can contribute dramatically to more rational, economical production systems. In introducing automation, it is important to consider how the design of products and parts should be reexamined, and what kind of improvements should be made. The following are some guidelines for such reexamination:

1. *Reduction of the number of component parts.* Consider how to simplify the structure of the product, reducing the number of component parts. If the number of parts is reduced, needless to say, the amount of part fabrication and processing will decrease, often resulting in major cost reductions.
2. *Standardization and reduction of the varieties of parts.* Standardize parts and materials and reduce the variety as much as is feasible.
3. *Design for easy automation.* Simplify the shape of parts as much as possible. Moreover, when simplifying, check if there is a problem with identifying front vs. back or right vs. left, and consider whether in the production there may be problems lining up, grasping, or positioning the parts, or disentangling work pieces. Examine whether the structure of the part

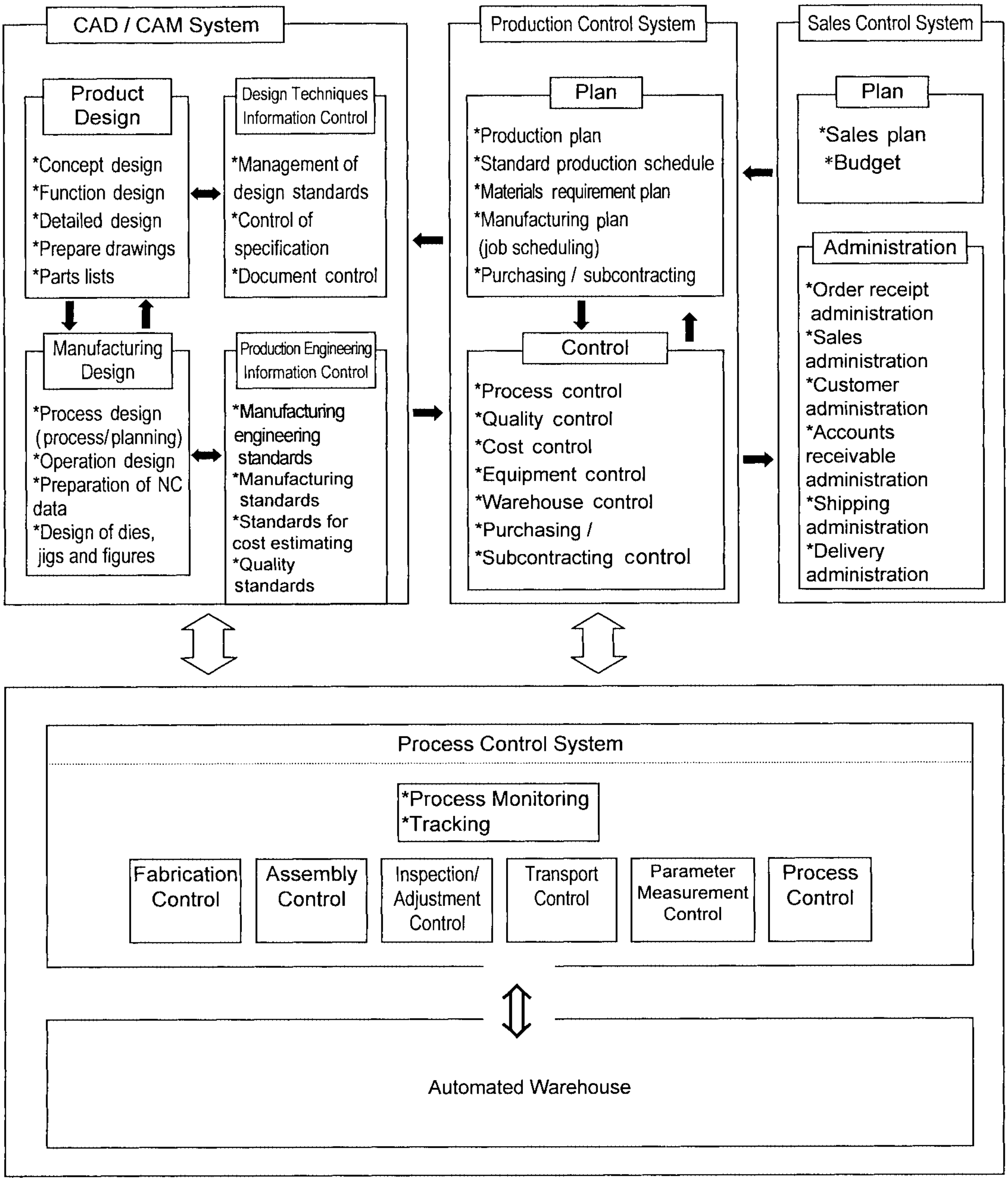
CAD / CAM System
Product Design
*Concept design
*Function design
*Detailed design
*Prepare drawings
*Parts lists
Design Techniques Information Control
*Management of design standards
*Control of specification
*Document control
Manufacturing Design
*Process design (process/planning)
*Operation design
*Preparation of NC data
*Design of dies, jigs and figures
Production Engineering Information Control
*Manufacturing engineering standards
*Manufacturing standards
*Standards for cost estimating
*Quality standards
Production Control System
Plan
*Production plan
*Standard production schedule
*Materials requirement plan
*Manufacturing plan (job scheduling)
*Purchasing / subcontracting
Control
*Process control
*Quality control
*Cost control
*Equipment control
*Warehouse control
*Purchasing /
*Subcontracting control
Sales Control System
Plan
*Sales plan
*Budget
Administration
*Order receipt administration
*Sales administration
*Customer administration
*Accounts receivable administration
*Shipping administration
*Delivery administration
Process Control System
*Process Monitoring
*Tracking
Fabrication Control
Assembly Control
Inspection/ Adjustment Control
Transport Control
Parameter Measurement Control
Process Control
Automated Warehouse

FIGURE 14.5.3 Information structure for an FA production system.

creates problems in the required production steps such as assembly, attachment, or handling. Any problems discovered at this stage should be solved through design improvements.

4. *Accuracy/precision of parts.* In assembly operations, greater accuracy often results in the reduction or elimination of manual fitting or adjustment steps.

Necessary Conditions for Automation and Establishing Target Values

When introducing automation, it is important to clarify the prerequisites. In the investigation for that purpose, the following points must be studied anew in their role as necessary conditions for automation. In addition, they must be considered not only in the present situation but in terms of expected conditions years in the future.
System parameters:

- Types or models of products produced
- Production pace
- Cycle time
- Production lot size
- Number of setups
- Level of automation
- Production lead time
- Quality requirement
- Others

Level of Automation and Examination of the Process

Study of the Process. From the viewpoint of implementing automation, the following process-related matters must be examined:

1. *Processing method.* Processing methods must be examined and alternatives sought that make the introduction of automation easier—for example, a decision to "change from machining to fabrication by press." Changing the processing method often results in the need for changes to component parts (e.g., to their shape, material, or preconditioning).
2. *Workflow.* Production pace, cycle time, production lot size, the elimination or combination of process steps, as well as the sequence of process steps, must all be investigated. In addition, layouts must be studied and the possibility of one operator handling multiple machines or multiple process steps (or stations) considered.
3. *Production line design.* Line configuration, cycle time, line balance, and so forth must all be examined.

Study of the "Human-Machine" Relationship. Based on a thorough understanding of the characteristics of the operators and equipment, automation is planned which is well-balanced in terms of the cost-performance of human operations versus machine operations.

In the past it was expensive and technically difficult to attempt to mechanize or automate activities such as decision making, selection, checking, and adjusting, all of which had been done by operators. More recently however, with the advances in computer science, automation has become practical for simple decision making, identification, and adjustment. At present, the important characteristics of humans and machines, and their differences in regards to automation, can be summarized as follows:

- *Identification/judgment.* People have eyes. Machines, on the other hand, obviously do not, and thus they are not suited to grasping the relationship of locations separated by empty space. However if a part is always delivered to a prescribed location in a prescribed orientation, identification and judgment by machines becomes possible.
- *Degrees of freedom.* People have two hands and many joints, resulting in dozens of degrees of freedom. In contrast, the number of degrees of freedom for robots, at the present time is only about four to six in actual practice.
- *Convertibility.* People are "convertible" (i.e., they can be reassigned to another process fairly readily). Machines, on the other hand, are highly specialized and are difficult to convert to another function.

Study of the Operations of Each Process to Identify Targets for Automation. Next, taking the special characteristics of operators and machines into account, the questions of which operations to automate and to what extent they should be automated must be examined. A list of operations that are frequently considered targets for potential automation follows, along with the current situation as to the use of automation in each area.

1. *Production instructions (work orders, process plans, etc.).* Following a production schedule that has been established beforehand, automation can be applied to loading the NC tape, presetting cutting tools, and other such setup activities. LANs are now widely used as the information transmission system, with optical fiber adopted broadly as the actual transmission medium.

2. *Setup.* Automation can be applied to the following setup steps:
    - Setup of tools, fixtures, and jigs
    - Selection and setup of workpieces
3. *Part and workpiece feeding (storage, alignment, transport, and single-part selection).* In automating equipment, one of the first requirements is to "grasp" the item automatically. That seems straightforward, but even that one step often presents difficulties. Moreover, to feed an object to a machine, the various actions of selecting a single part and aligning, grasping, and inserting it are all required. Examples of automated feeding equipment in common use today would include *parts feeders* and *magazine feeders.* Objects of the following types generally lend themselves to being easily transferred with automatic feeding equipment:
    - Small, hard parts which are easy to align
    - Objects with accurate dimensions
    - Objects generally not needing inspection or repair
    - Objects that can be loaded in magazines

    Conversely, it is difficult to align and grasp the following types of objects, and they are generally not suitable for automatic feeding:
    - Objects that arrive jumbled together
    - Objects that have inconsistent shapes
    - Soft objects

    Accordingly, if the feeding of parts and materials is to be automated, those parts and materials must be designed so that tangling, overlapping, breakage, and deformation can be avoided.
4. *Insertion/removal.* Robots are widely used for these activities.
5. *Positioning and clamping of workpieces.* When positioning workpieces, generally fixtures and jigs are used, but it is essential that a precise, repeatable location be established for the workpiece, so that it can be properly machined. In such cases, the pros and cons of using a traveling fixture (pallet), a locator pin, or other positioning method should be evaluated.

6. *Selection of operation methods and setting of parameters.* For machine tools, parameters such as of depth of cut, feed rate, and cutting speed must all be set. In the case of NC machine tools, these settings are provided automatically by the NC tape and/or instructions directly from a computer.
7. *Control and programmable controllers.* Instead of panels of relays as in the past, programmable controllers (PCs) are now used in many applications to control the order and content of process steps. The data processing speed of the latest PCs is extremely fast, and they have advanced arithmetic sequencers and other features. In fact, the capacity of these PCs in terms of operation instructions rivals that of microcomputers, and the number of I/O points they offer ranges from 20 to 2000.
8. *Measurement/inspection.* Operations such as work positioning, comparing with nominal values, reading of scales, calculating, displaying and recording data, analyzing quality, and disposition of completed work are readily done through automated systems. Recently, even automated in-line inspection is performed in many cases.
9. *Transport of objects (transfer to the next processing station).* Transports are classified as *continuous transports* (such as conveyers) and *intermittent transports* (robots, etc.) Recently, robots have become widely used. With robots, the layout can be arranged so that one robot can handle multiple transfer tasks (e.g., even for multiple machines) resulting in effective applications that save space and cost.
10. *Cleanup.* Automated equipment can handle the disposal of chips and excess coolant, the removal of tools, fixtures, and jigs, and the cleaning of the machines.

CONCLUSION AND FUTURE TRENDS

In summary, a key point in automation is to carefully consider the linkage between the "front-end" processing and the "back-end" processing. For example, it would be ideal if products moved from the front end of the process to the back end stations, neatly lined up. Moreover, it is desirable for lot sizes to be equal and for synchronized production to be utilized. Based on thorough research, the process operations to be automated and the method of automation must be determined. Then, the preparatory work must turn to defining equipment specifications and the conditions for introduction of the equipment.

FURTHER READING

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BIOGRAPHY

Kiyomi Nakamori graduated from the Tokyo Agricultural and Engineering University in 1964. After working for Olympus for several years in the areas of quality control and manufacturing engineering, he joined JMA Consultants in 1970. He has consulted in the areas of quality control (especially "design of experiments"), value engineering (VE), cost control systems, and the design of manufacturing systems. He has also worked with many client firms to improve the efficiency of their product development and design departments. Since 1980 he has been involved in guiding firms in their adoption of Factory Automation. He is the author of several books on subjects such as cost management, management engineering, and the efficiency of product design operations.

CHAPTER 14.6

INDUSTRIAL PROCESS CONTROL

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This chapter will discuss the evolution of industrial process control and some of its important applications—and in particular computer numerical control. These applications are pervasive in high, medium, and low production throughout the wide spectrum of modern industrial processes. The chapter begins with some of the basic concepts and definitions of process control. We then describe the two principal types of modern industrial process controllers: programmable logic controllers and digital computer controllers. Included in our coverage of computer control is a discussion of the software and hardware issues that allow computers to be connected to industrial processes. Computer process control is an important tool in the automation of manufacturing operations.

BASICS OF PROCESS CONTROL

Industrial process control is concerned with the automatic regulation of unit production operations and their associated equipment. It also includes the integration of the unit operations into larger production systems and the economical management of these systems. In this chapter, we examine the techniques and technologies of process control as they are applied in the manufacturing industries.

Control of an industrial process is usually accomplished using one or more feedback control systems. In its simplest form, a *feedback control system* is a closed-loop system in which the output (controlled) variable is compared to the set point (input) and any difference between the two is used to drive the output toward the set point. As illustrated in Fig. 14.6.1, a feedback control system consists of six basic components: (1) set point, (2) process, (3) output, (4) feedback sensors, (5) controller, and (6) actuators. The *set point* is the input signal that represents the desired value of the output. The *process* of interest here is usually a manufacturing operation. The *output* is a function of the process. A *sensor* is used to measure the output variable and close the loop between input and output. Sensors accomplish the feedback function in a feedback control system. Finally, the *controller* compares the output with the desired input and makes adjustments in the process to reduce the difference between them. The adjustments are made by means of one or more *actuators,* which are hardware elements that physically accomplish the control actions directed by the controller.

A positioning system is a common example of a feedback control system. Its typical function in a manufacturing operation is to move a workpart to a desired location relative to a

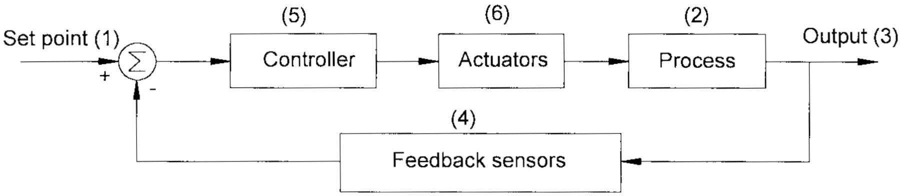

FIGURE 14.6.1 A feedback control system.

processing tool or workhead. In operation, the positioning system is directed to move the worktable to a certain location defined by coordinate values in an axis system (for example, x and y values in a Cartesian coordinate system). For an x-y positioning table, two feedback control systems are required, one for each axis. A common actuator for each axis is an electric motor driving a leadscrew, as in Fig. 14.6.2. The controller transmits a signal corresponding to a coordinate value (for example, x-value) to the motor to drive the leadscrew. When the leadscrew rotates, this rotation is converted into linear motion of the table. As the table moves closer to the desired coordinate value, the difference between actual x-position and input x-value is reduced. The actual position is sensed by a feedback sensor, such as an optical encoder. The controller continues to drive the motor until the actual table position is equal to the desired input position.

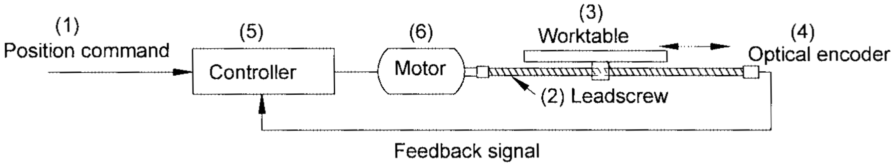

FIGURE 14.6.2 A one-axis positioning system consisting of a leadscrew driven by an electric motor.

Open-Loop Versus Closed-Loop Systems

As stated in our definition, a feedback control system is a *closed-loop system,* in which the feedback signal closes the loop between output and input. Some automated systems operate without the feedback loop; this type of operation is called an *open-loop system,* as in Fig. 14.6.3. Open-loop systems are generally simpler and less expensive than closed-loop systems. They are appropriate for applications in which: (1) the actions accomplished by the system are simple, such as closing an electrical switch; (2) the actuating function is highly reliable; and (3) any reaction forces opposing the actuation are minimal. If these characteristics do not apply, then a feedback control system is probably more appropriate.

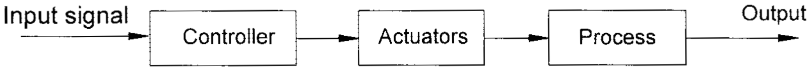

FIGURE 14.6.3 An open-loop control system.

As an example of the open-loop case, consider a positioning system consisting of a stepper motor whose output shaft is attached to a leadscrew that moves a worktable. The diagram for this system would be similar to the previous closed-loop positioning system in Fig. 14.6.2, but the feedback sensor loop would be absent. The controller transmits a sequence of pulses to the stepper motor, and this drives the leadscrew to rotate a precisely metered fraction of a turn for each pulse. Thus, for each pulse the worktable is moved a known linear distance. To move the table to a given position, the corresponding number of pulses is sent to the motor. In the proper application, whose characteristics match the preceding list, an open-loop positioning system operates with high reliability.

Machine Programming

In many process control situations, the purpose of the control system is simply to maintain the output variable at a certain desired value throughout the process. This situation is typical of the process industries, such as chemicals and petroleum, in which the production runs are long, the physical state of the product is a fluid, and the product is made in large volumes. In the manufacturing industries, by contrast, the product is a discrete part that is made by performing a sequence of processing steps on a starting workpiece. The typical function of the control system is to direct the equipment to carry out each step correctly and in the correct order. In this case, each controlled variable takes on a different value in each step. The sequence of steps and the details of each step (including the values of each controlled variable) are determined by a program of instructions. In the simplest systems, the processing steps comprise a well-defined work cycle that is repeated with little or no deviation from cycle to cycle. Mass production operations such as automatic screw machine cycles, stamping press operations, plastic molding, and die casting fall into this category. These processes have been used for decades, and the equipment has traditionally been controlled by hardware components such as cams, electromechanical relays, and limit switches. In addition to controlling the equipment, these components also comprise the program of instructions which determines the sequence of steps in the work cycle.

These devices were quite adequate for the modest control requirements of these processes; however, modern controllers are based on computers. Computer-based industrial controllers can be classified into two categories: (1) *programmable logic controllers* and (2) *digital computer controllers* such as microcomputers and minicomputers. Instead of cams and switches, the programs for computer controlled equipment are contained on magnetic tape, diskettes, computer memory, or other modern storage technologies. Computer control allows improvements and upgrades to be made in the control programs, such as the addition of control functions not foreseen during initial equipment design. These kinds of control changes are difficult to make with the previous hardware devices.

PROGRAMMABLE LOGIC CONTROLLERS

Many industrial process control systems receive sensor inputs in the form of binary signals and respond by turning on and off motors, switches, and other binary actuators. These control devices can take either of two possible values, 1 or 0, which mean ON or OFF, workpart present or not present, high or low voltage level, and so on. A widely used industrial controller capable of receiving and sending binary as well as other types of sensor and control signals is the *programmable logic controller* (PLC). A programmable logic controller can be defined as a microcomputer-based device that uses stored instructions in programmable memory to implement logic, sequencing, timing, counting, and arithmetic control functions, through digital or analog input/output modules, for controlling various machines and processes. Prior to the introduction of the PLC around 1970, hard-wired controllers consisting of electromechanical relays, coils, counters, timers, and similar discrete components were used to accomplish this type of industrial control.

As shown in Fig. 14.6.4, the major components of a PLC are: (1) *input and output modules,* which collect data from and send command signals to the industrial equipment; (2) *processor,* which is the central processing unit (CPU) that executes the sequencing and logic functions based on the input signals received; (3) *memory,* which is connected to the microprocessor and contains the control program that defines the sequencing and logic functions; and (4) *power supply,* which is usually 115 volts ac. In addition, (5) a *programming device* is used to enter the program into the PLC or to edit an existing program. The programming device is usually detachable from the PLC.

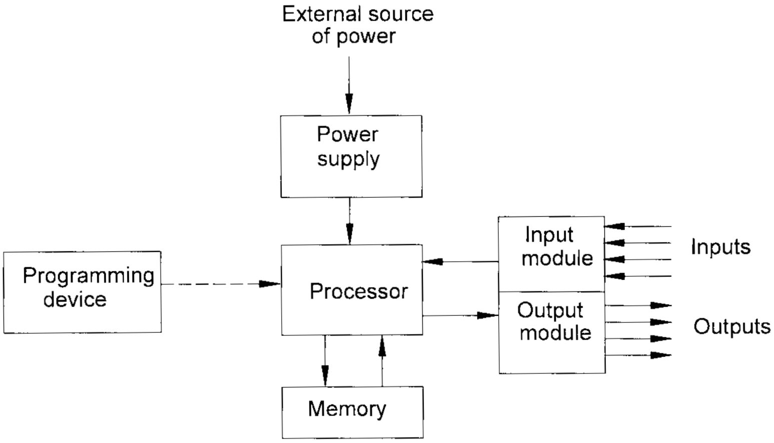

FIGURE 14.6.4 Major components of a programmable logic controller.

Ladder logic is the most commonly used method for programming a PLC. *Ladder logic* is a diagramming technique in which the various logic elements and components are portrayed on the horizontal rungs of a ladder and the rungs are connected to two parallel vertical lines which supply power to the components. Figure 14.6.5 shows a portion of a typical ladder logic diagram that might be used in an industrial controller. The ladder logic diagram can be entered into the programming device using programming statements that construct the logic elements and components on each rung. As each statement is entered, the programming device displays the additions to the ladder logic diagram.

Compared to the electromechanical relays that preceded the PLC in the evolution of industrial controllers, programmable logic controllers have the following advantages: (1) it is easier to program a PLC than to wire the relay control panel; correcting or enhancing an existing program is also easier; (2) PLCs can be reprogrammed for a new application, whereas conventional hard-wired controls must be rewired; the hard-wired controllers are often scrapped rather than reused because of the difficulty in rewiring; (3) interfacing a PLC to other computer systems is easier than with conventional controls; (4) less floor space is required, and (5) PLCs are more reliable and easier to maintain than hard-wired controllers.

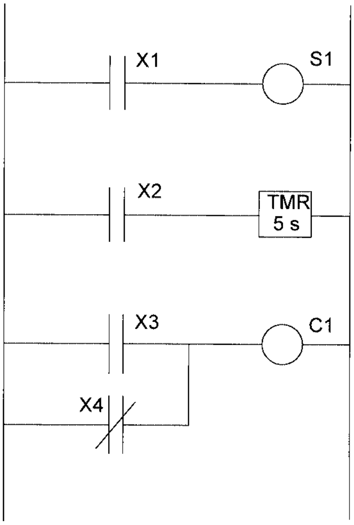

FIGURE 14.6.5 An example of a portion of a ladder logic diagram.

DIGITAL COMPUTER CONTROLLERS

Control of industrial processes by digital computers can be traced to the oil refinery and chemical processing industries in the late 1950s and early 1960s. The production processes in these industries are characterized by large numbers of variables and associated control loops for each variable. They had traditionally been controlled by analog devices, typically requiring one or more analog devices dedicated to each feedback loop. Each loop had its own set point value and in most instances operated independently of all other loops. Any coordination of the system had to be accomplished in a central control room, where workers made adjustments in the individual settings to attempt to achieve a semblance of stability and economy in the process. The hardware cost for all of the control loops was substantial, and the human means of coordination was far from optimal.

With the commercial development of the digital computer in the 1950s, the opportunity presented itself to replace some of the analog elements with a computer. Not all of the components in each loop could be replaced, but some of them could, such as the analog controller that performed the conventional proportional-integral-derivative (PID) control functions, the recording and display units, and the comparator that compared the measured output to the set point. If these devices could be replaced for all of the control loops in the system, the cost of the digital computer might be justified. Operating on a time-shared, sampled-data basis so that each loop could be serviced, the computer would receive the measured values of the process variables, make the calculations associated with the controller functions, and send back commands to the various actuators and process interface devices. It would also maintain records of process performance.

This form of control was called *direct digital control* (DDC, for short). The central computer was "directly" linked to the production process, hence the name for this control type. Owing to the high cost of mainframe computers in those early days, direct digital control could be cost-justified only for very large systems—ones with numerous control loops so that the savings in analog hardware components would exceed the price of the mainframe.

DDC was originally conceived as a more efficient way to carry out the same types of control actions as the analog elements it replaced. However, the digital computer is capable of doing much more than simply mimic the operation of a group of analog controllers. Three enhancements of this early form of computer control have since been developed:

1. *Wider variety of control algorithms.* Analog controllers are somewhat limited in terms of the scope of computations they can perform. Generally, their operations are restricted to some combination of PID control. The digital computer is considerably more versatile in the control calculations it can be programmed to execute. For example, optimal control algorithms can be accomplished on the control loops for which they are appropriate.

2. *Editing and modifying the control algorithm.* It is relatively easy to change the control algorithm, if that becomes necessary, simply by reprogramming the computer. Altering the analog control loop is likely to require hardware changes that are more costly and less convenient.

3. *More than loop control.* As long as the computer is connected to every loop, why not program it to integrate the information from all of the signals and use some optimizing algorithm to manage the entire process? The computer would thereby make the required adjustments in the set points for the individual feedback loops, rather than the crew of workers in the central control room.

These enhancements of direct digital control have rendered the original DDC concept obsolete. Today, computers perform all of the functions just described and more, and computer technology itself has progressed dramatically so that much smaller and less expensive (yet more powerful) computers are available for process control than the large units of the early 1960s. Starting in the early 1990s, personal computers have been used as controllers for industrial operations. PCs had previously been used as an operator interface for PLC-based systems, but now they are competing with PLCs for the controller function itself. Indeed, the distinction between PCs and PLCs has become blurred as personal computers are becoming equipped to carry out control functions and PLCs are being equipped to perform data processing functions. Conditions that tend to favor the use of personal computers as process controllers include: (1) the operating environment where the computer is installed is not harsh,

(2) there is a need for a high level of operator interface, (3) a significant amount of data processing must be done for at least some of the control loops, and (4) the use of the PC's open protocol does not compromise the security of the system.

TYPES OF COMPUTER PROCESS CONTROL

Computers are used in a variety of ways for controlling and observing the manufacturing process. Three basic categories can be identified: (1) *process monitoring,* (2) *preplanned control,* and (3) *supervisory control.* Common industry practice often combines more than one type in a single process control installation.

Process Monitoring

Computer process monitoring involves the use of a digital computer to collect and record data on the process and associated equipment. The data collected by the computer can be classified as follows:

- *Process data.* These are measured values of input and output variables that indicate process performance.
- *Equipment data.* This refers to measured or calculated values that indicate machine status, such as machine utilization, tool-change statistics, and machine malfunction diagnostics.
- *Product data.* Measured or counted data relating to product quality and production rates. Strictly speaking, process monitoring is not really a type of computer process control, because the computer does not directly control the process. Control of the process remains in the hands of human operators, who manage the process using the collected data and computer-prepared reports for guidance.

Preplanned Control

In this category, the computer directs the process or equipment to perform a predetermined sequence of operating steps. The control sequence is defined by means of a program that must be prepared in advance. The program specifies the order in which the steps are to be carried out. It is likely to include If-Then statements to cover the various processing conditions and contingencies that might be encountered. Preplanned control often uses feedback control loops to verify that each step in the operating sequence has been properly executed before proceeding to the next step. However, in some cases, feedback is not required, and such systems execute the processing sequence in an "open-loop" fashion. Preplanned control goes by various names in industry, and some examples will help to illustrate this control mode:

- *Numerical control.* In numerical control, the motions of a tool relative to the object being processed are controlled by a (preplanned) program. Owing to its importance among industrial process control systems, the topic of numerical control is discussed in a later section of this chapter.
- *Sequence control.* This refers to a form of preplanned control that usually includes a combination of sequencing and logic control. A *sequencing system* operates by means of internal timers to determine when changes in process parameters will occur. The changes are typically ON/OFF functions. *Logic control* refers to a control mode in which logical decisions and actions about the process are taken in response to events that have occurred in the production system. The output signals of the controller are determined by the signals

indicating process status. Sequence control is widely used for industrial process control and is often accomplished by programmable logic controllers.

- *Program control.* This control type is most commonly used in the process industries. It refers to applications in which the computer is used to start up or shut down complex industrial processes, or to change over the process from one product grade to another, or to control the process through a sequence of processing steps in chemical batch processing. In program control, the objective is to guide the process from one operating condition to the next by making appropriate changes in the process variables.

Supervisory Control

Supervisory control denotes a control system in which the computer is programmed to optimize some overall objective function for the process. The objective function, or *index of performance* as it is sometimes called, is usually based on one or more economic criteria such as maximum production rate, or minimum cost, or optimum quality. Supervisory control is often superimposed on other control modes previously discussed. The other controls are connected directly to the process, while supervisory control directs the operations of these process-level control systems, as suggested by the diagram in Fig. 14.6.6. Several control strategies are used in supervisory control to optimize the process. In the following list, we survey the most prominent control categories.

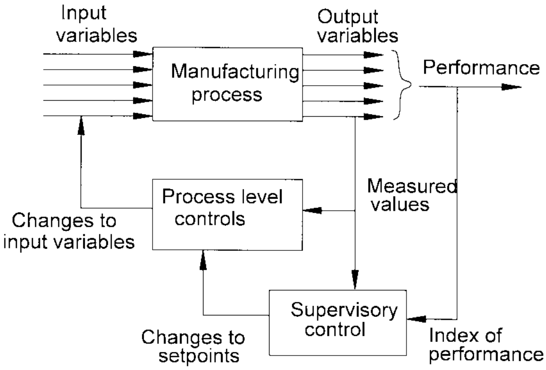

FIGURE 14.6.6 Supervisory control superimposed on other process-level control systems.

- *Regulatory control.* The objective here is to maintain process performance at a certain level, or within a given tolerance band of that level. This is appropriate, for example, when the performance attribute is some measure of product quality, and it is important to keep the quality at the specified level or within a specified range. As indicated in Fig. 14.6.7, regulatory control is to the overall process what feedback control is to an individual control loop in the process.
- *Feedforward control.* Feedforward control attempts to anticipate the effect of disturbances that will upset the process by sensing them and compensating for them in advance of the upset. As shown in Fig. 14.6.8, the feedforward control elements sense the presence of a disturbance and adjust a compensating parameter that cancels any effect the disturbance will have on the process. In the ideal case, full compensation results. However, full compensation is unlikely due to imperfections in feedback measurements, actuator operations, and controller algorithms, and so feedforward control is usually combined with feedback control, as shown in the block diagram.

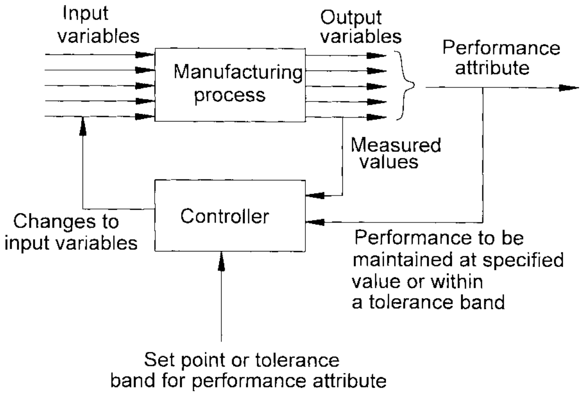
Input variables
Output variables
Performance attribute
Manufacturing process
Measured values
Controller
Changes to input variables
Performance to be maintained at specified value or within a tolerance band
Set point or tolerance band for performance attribute

FIGURE 14.6.7 Regulatory control.

- *Steady-state optimization.* This term refers to a class of optimization problems where the process is characterized by the following three conditions: (1) there is a well-defined economic performance criterion (index of performance) such as product cost, production rate, or process yield; (2) the relationships between the process variables and the performance criterion are known; and (3) the values of the system parameters that optimize performance can be mathematically determined. In these cases, the control program is designed to make adjustments in the process variables to drive the process toward the optimal state. The control system operates in an open-loop manner, as indicated in Fig. 14.6.9. A variety of mathematical techniques exist for solving steady-state optimal control problems; these include differential calculus, calculus of variations, linear programming, dynamic programming, and others.
- *Adaptive control.* Steady-state optimal control operates as an open-loop system. Adaptive control can be considered as a combination of feedback control and optimal control. As in feedback control, the relevant process variables are measured; and as in optimal control, the control algorithm attempts to optimize some relevant index of performance.

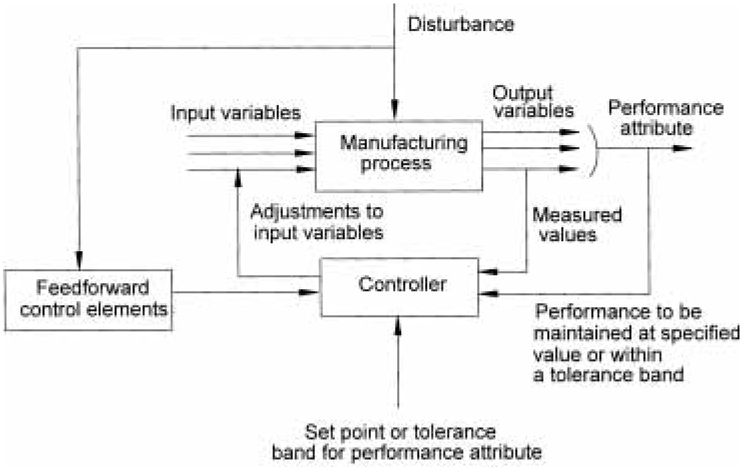
Disturbance
Input variables
Output variables
Performance attribute
Manufacturing process
Adjustments to input variables
Measured values
Feedforward control elements
Controller
Performance to be maintained at specified value or within a tolerance band
Set point or tolerance band for performance attribute

FIGURE 14.6.8 Feedforward control combined with feedback control.

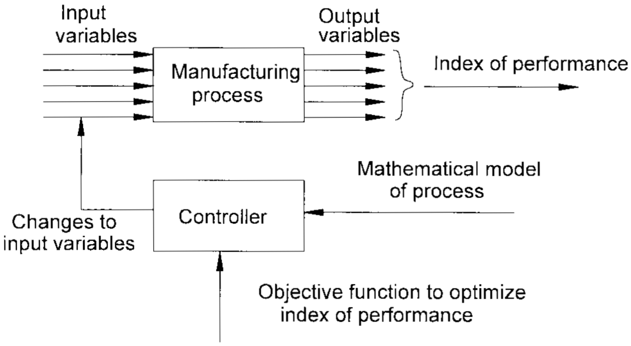
Input variables
Output variables
Manufacturing process
Index of performance
Mathematical model of process
Controller
Changes to input variables
Objective function to optimize index of performance

FIGURE 14.6.9 Steady-state (open-loop) optimal control.

What distinguishes adaptive control from the other two types is its special capability to cope with a time-varying environment. In both feedback control and steady-state optimal control, the environment is assumed to remain constant. Otherwise, system performance is degraded. An adaptive control system is designed to compensate for its changing environment by monitoring its own performance and altering some aspect of its control mechanism to achieve optimal or near-optimal performance. In a manufacturing process, the term *environment* refers to the day-to-day variations in raw materials, tooling, atmospheric conditions, and the like. As depicted in Fig. 14.6.10, three functions characterize the operation of an adaptive control system: (1) *identification*—the current performance of the system is measured or computed based on data collected from the process; (2) *decision*—the control system figures out (computes by some preprogrammed logic) what changes in its input variables or internal parameters should be made to improve performance; and (3) *modification*—the decision is implemented by making the adjustments indicated. These adjustments are typically made by altering the internal control parameters of the process-level controller, as illustrated in the block diagram, or by changing the values of the inputs to the process.

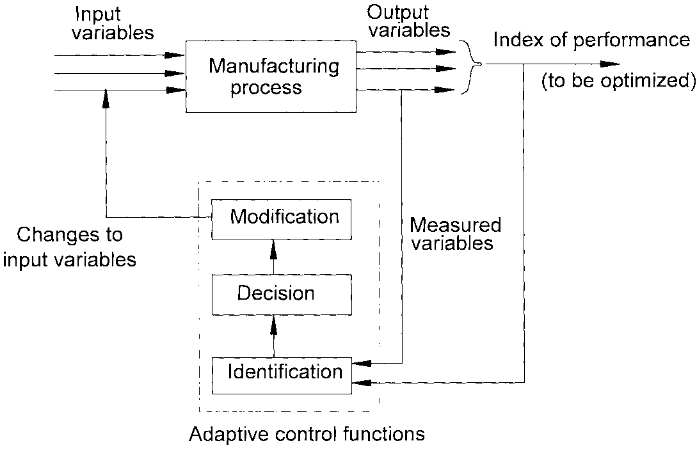
Input variables
Output variables
Manufacturing process
Index of performance
(to be optimized)
Modification
Changes to input variables
Measured variables
Decision
Identification
Adaptive control functions

FIGURE 14.6.10 Configuration of an adaptive control system.

- *Search techniques.* These are used for a special class of adaptive control problem in which the decision function cannot be sufficiently defined; specifically, the influence of the input variables on performance is not known, or not known well enough to utilize adaptive control as previously described. Accordingly, it is not possible to determine what changes to make in the input variables or internal parameters of the system in order to effect the desired improvement in performance. Thus, a search strategy is employed in which systematic changes are made in the input variables to observe what effect these changes have on the output variables. Based on the results, the appropriate changes are made in the inputs so that system performance will be improved. The most familiar search strategies are those based on the use of gradients, which indicate which input variables will provide the maximum improvement in the index of performance for the process.
- *Other specialized techniques.* These include learning systems, expert systems, and other artificial intelligence approaches used in process control.

REQUIREMENTS OF PROCESS CONTROL SOFTWARE

Programming for computer process control is distinguished from data processing or engineering and scientific applications by several requirements, all concerned with the need to communicate with the process on a real-time basis. The software requirements can be stated as follows:

- *Timer-initiated events.* The computer must be able to manage events that occur in clock time, some at regular intervals (such as sampled-data values of process variables) and others at distinct points in time (such as lowering the furnace temperature at the end of a heat-treat cycle).
- *Process-initiated interrupts.* The computer must be programmed to respond to incoming signals from the process, so that it interrupts its regular program execution to service the process.
- *Computer commands to process.* In addition to accepting incoming signals from the process, the computer must be capable of transmitting control signals to the process, to actuate hardware devices or to adjust a set point in a control loop.
- *System- and program-initiated events.* The process control system rarely stands alone. It is becoming increasingly common for computer systems to be interconnected in networks, to transmit data and instructions between the systems; for example, data on machine utilization or instructions to begin a new production order.
- *Operator-initiated events.* Finally, the computer must be able to accept input from the (human) operator, for program editing, startup instructions, or emergency stop.

Most of these requirements can be satisfied by designing the computer system and associated software so that its current operations (whatever software it is currently executing) can be interrupted by events that have higher priority. This kind of system is called an *interrupt system.* In the following paragraphs, this and other features of industrial process control software are discussed.

Priority Interrupt System

All computer systems have interrupt capability (if nothing else, the power can be shut off). A more sophisticated interrupt system is required in process control applications. An *interrupt logic system* is a computer control feature that permits the execution of the current program to be suspended so that another program or subroutine can be executed in response to an incoming signal indicating a higher priority event. When the interrupt signal is received, control is transferred to a predetermined subroutine that is designed to deal with the specific interrupt. The location and status of the current program is remembered so that its execution can be resumed after the interrupt has been serviced. Interrupt conditions can be classified as *internal* or *external.* Internal interrupts are generated by the computer system itself, and include timer-initiated data recording and commands to the process. External interrupts are events that are external to the computer system, such as an out-of-tolerance process variable or an operator input. The reason why an interrupt system is required in process control is so that more important programs will be executed before less important ones, and so that higher-priority functions can interrupt functions with lower priorities. Accordingly, the possible functions performed by the control computer must be prioritized. A typical ranking of functions might be as shown in Table 14.6.1. The actual number of priority levels, and the relative importance of the functions, must be designed for the individual process control situation. For example, emergency shutdown of a process for safety reasons would be an operator input; yet it would occupy a very high priority level. Most operator inputs would have low priorities.

TABLE 14.6.1 Possible Priority Levels in an Interrupt System

Priority level	Computer function
1 (lowest priority)	Most operator inputs
2	System interrupts
3	Timer interrupts
4	Commands to process
5	Process interrupts
6 (highest priority)	Emergency stop (operator input)

Decision Making

Decision-making capability is included in a control program as instructions that execute any of several alternative control actions, depending on conditions and circumstances. A typical case is a flexible manufacturing cell that is programmed to process several different part styles, and the system must execute the appropriate processing steps for each style. A similar example is a robotic spot welding line in an automobile final assembly plant. The robots are programmed to perform different welding cycles for different body styles, such as two-door versus four-door sedans. As each car body enters a given welding station, sensors identify the body style, and the robots perform the correct welds for that style.

Diagnostics

Another desirable feature of the computer system is the capability to identify the reason behind any failures or malfunctions that may beset the process. These occurrences can result in costly downtime and lost production. The process must often be stopped and repaired by humans. The typical diagnostics system has three modes of operation: (1) *status monitoring,* in which the system observes and records the important process and equipment variables; (2) *failure diagnostics,* during which a malfunction or failure has occurred and the sensed variables must be interpreted and the problem diagnosed; and (3) *recommended repairs,* in which the system provides a suggested procedure to be used by the repair crew. Recommendations are often based on the collective knowledge of experts on the particular equipment or process. In some applications, diagnostics systems are designed to anticipate the occurrence of failures by observing subtle changes and trends in the operating characteristics of the process and predicting possible malfunctions that may result from these changes.

Error Detection and Recovery

The use of a diagnostics system usually presumes that human operators will help in diagnosing the malfunction, make the necessary repairs, and restart the operation. With the increasing use of computers for process control, the computer is being called on not only to detect the problem, but also to perform the necessary steps to repair and restore the system automatically (without human involvement). *Error detection and recovery,* as this capability is called, consists of two phases: (1) *error detection* and (2) *error recovery.* Error detection involves the use of sensors interfaced to the process and the proper interpretation of the sensor signals by the computer system to identify when an error has occurred and the nature of the error. Typical errors in process control include equipment and tooling failures, significant variations in raw materials, and human mistakes (for example, entering an incorrect identification code for the product). When an error in the process is detected, this interrupts the normal process control functions, so that the error recovery procedures can be executed. In error recovery, the required corrective actions are taken for the particular error so that the normal operating mode can be resumed. Some of the possible recovery procedures are: automatic tool change when a tool breaks or wears out; abandoning further processing of the workpart if it has been damaged during the operation; and compensation for variables that have suddenly changed. If the same recovery procedure must be invoked on several successive cycles, it usually means that a systematic error is occurring, and a human operator must be called. The problems in designing an error detection and recovery system are: (1) anticipating the variety of possible things that can go wrong in the process; (2) developing the appropriate sensor package to reveal these errors when they occur; and (3) devising appropriate procedures that will either correct or compensate for the errors. These problems are usually very specific to the individual process.

COMPUTER INTERFACE HARDWARE

For process control, the computer must collect data from and transmit command signals to the manufacturing operation. The types of data and signals communicated between the computer and the process vary, depending on the sensors and actuating devices used. Three types of data, illustrated in Fig. 14.6.11, can be distinguished: (1) *continuous analog signals,* (2) *discrete binary data,* and (3) *discrete data not restricted to binary values.* Continuous analog signals are variables that can assume any of a continuum of values (within some practical range) and which vary over time. Examples in process control applications include position, force, flow rate, temperature, pressure, and velocity. Discrete binary variables can assume either of two possible values, usually on or off, opened or closed, and so on. Examples include: voltage to an electric motor on or off, a valve open or closed, and contact or no contact of a limit switch. Discrete data other than binary have multiple values, these values being limited to certain discrete, usually integer, levels. The data sometimes take the form of an electrical pulse train, a series of pulses that can be counted to obtain the data value. Many digital transducers (sensors) operate in this way. The following paragraphs discuss many of the interface hardware devices used to communicate these data between the computer and the process it controls.

Sensors and Transducers

These devices are used for collecting data from the manufacturing process. A *sensor* is a device that detects the physical variable of interest. A *transducer* is a device that converts one type of physical quantity to another, such as temperature to electrical voltage. The reason for making the conversion is to evaluate the signal more conveniently. A sensor and transducer are often combined to obtain a *measuring device* capable of measuring a physical variable and

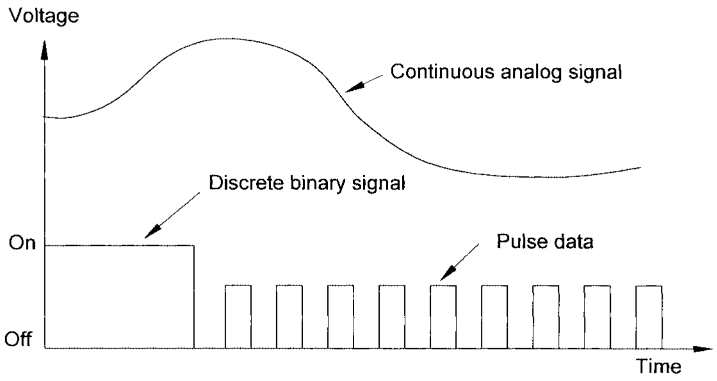

FIGURE 14.6.11 Three types of manufacturing process data.

emitting an electrical (usually) signal proportional to the value of the variable. Some of the desirable features of a measuring device for process control include: accuracy and precision, speed of response, reliability, minimum drift, and ease of calibration. Few measuring devices possess all of these features, and the process control designer must usually select among a variety of available sensor systems for the given application. A list of common sensors and measuring devices is presented in Table 14.6.2.

Actuators. In industrial control systems, an *actuator* is a hardware device that converts a controller output signal into a change in a physical variable such as position or velocity.

TABLE 14.6.2 Common Sensors Used in Industrial Process Control

Sensor	Process variable measured
Accelerometer	Vibration
Ammeter	Electrical current
Bourdon tube	Pressure, vacuum
Infrared sensor	Temperature
LVDT*	Angular or linear displacement
Limit switch	Contact or no contact
Manometer	Pressure
Ohmmeter	Electrical resistance
Pyrometer	Temperature
Optical encoders	Rotational speed and displacement
Photometer	Illumination, light intensity
Pitot tube	Flow rate
Potentiometer	Voltage
Strain gage	Force, pressure, torque
Thermistor	Temperature
Thermocouple	Temperature
Venturi tube	Flow rate

* Linear-variable-differential transformer

TABLE 14.6.3 Common Actuators Used In Industrial Process Control

Actuator	Description
DC motor	A rotating electromagnetic motor whose input is direct current (dc).
Hydraulic piston	An assembly consisting of a piston inside a cylinder; the piston exerts a force and provides linear motion in response to hydraulic pressure.
Induction motor	A rotating electromagnetic motor whose input is alternating current (ac).
Pneumatic cylinder	An assembly consisting of a piston inside a cylinder; the piston exerts a force and provides linear motion in response to air pressure.
Relay switch	An on-off switch designed to open or close a circuit in response to an electromagnetic force.
Solenoid	A two-position electromechanical assembly consisting of a core inside a coil of wire; the core is usually held in one position by a spring, but when the coil is energized the core is forced to an alternate position.
Stepping motor	A rotary electromagnetic motor whose output shaft rotates in direct proportion to pulses received.

Because it changes one type of physical quantity, say electric current, into another type of physical quantity, say rotational speed of an electric motor, an actuator is a transducer. Depending on the type of power input used to amplify the controller output signal to the transducer, most actuators can be classified into one of three categories: (1) *electrical,* (2) *hydraulic,* and (3) *pneumatic.* A list of common actuators is presented in Table 14.6.3.

Analog-to-Digital Converters

As its name indicates, an *analog-to-digital converter* (ADC) is a device that converts a continuous analog signal into an equivalent digital value. Most process signals are continuous and analog in nature. In order for the computer to interpret the signals, they must be converted into digital form. Figure 14.6.12 illustrates the ADC process, showing how the continuous analog signal is converted into a series of individual data values capable of being interpreted by the computer. Operating features that distinguish ADCs include: *sampling rate* (the rate at which the continuous signal is sampled); *conversion time* (the time it takes to convert the signal into digital form); and *resolution* (the precision with which the analog signal is evaluated).

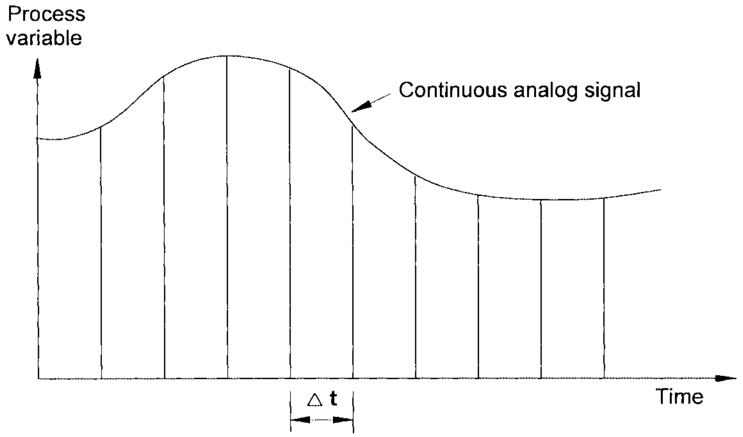

FIGURE 14.6.12 Analog signal converted into a series of discrete sampled data by an analog-to-digital converter.

Digital-to-Analog Converters

A *digital-to-analog converter* (DAC) performs the opposite function of an ADC; the DAC converts the digital output of the computer into a continuous (analog) signal for transmission to actuators that are driven by continuous signals. Digital-to-analog conversion consists of two steps: (1) *decoding,* in which the digital data output of the computer is converted into analog value, and (2) *data holding,* in which the analog value is made into a continuous signal (usually electrical voltage) that can be used by the analog actuator at the process. This two-step process is repeated at periodic intervals to obtain a step-wise analog signal as shown in Fig. 14.6.13.

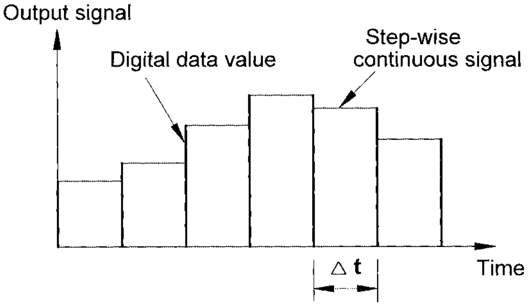

FIGURE 14.6.13 Digital output converted into a step-wise analog signal.

Contact Interfaces

Contact interfaces are of two types: *input* and *output.* A contact input interface is a device by which binary data are read into the computer. It consists of a simple contact device that can be either open or closed (on or off) to indicate the status of a limit switch, valve, motor, or other similar device related to the process. Scanning of these contacts by the computer is similar to the operation of a programmable logic controller. A contact output interface communicates on/off signals from the computer to the process. Based on the control algorithms programmed into the computer, the contact positions are set in either of two positions: ON or OFF. These positions are maintained until changed by subsequent events in the process. Hardware controlled by the contact output interface include alarms, indicator lights (on control panels), solenoids, and constant-speed motors.

Pulse Counters

Some of the data flowing from the process to the computer is in the form of pulse trains, most commonly electrical pulses, for example, from digital transducers. To illustrate a typical application, suppose the rotational speed of a motor is to be measured. The motor shaft is connected to an optical encoder, which generates a certain number of electrical pulses for each rotation. To measure rotational velocity, the pulse counter is used. It actually measures the time during which a specified number of pulses are received from the encoder. To determine velocity, the number of pulses is divided by the measured time and by the number of pulses per revolution of the optical encoder.

Pulse Generators

Pulse generators are used by the control computer to produce either (1) a specified number of pulses, or (2) a certain rate or frequency of pulses. In case (1), the specified number of pulses might be used to control the x-axis or y-axis of a positioning table. In case (2), the pulse rate (that is, the frequency of the pulse train) could be used to control the rotational speed of a stepping motor. A pulse generator operates by repeatedly closing and opening an electrical contact, to produce either a specified pulse count or a specified pulse rate.

COMPUTER NUMERICAL CONTROL

An important example of computer process control in industry is *numerical control.* Numerical control (NC) is the foundation for virtually all automated machine tools used in discrete product manufacturing. It also has many other applications. Numerical control involves the control of a machine by means of numbers and other symbols, collectively called the *part program* and coded in an appropriate format that can be interpreted by the machine control unit. In modern NC technology, the machine control unit is a microcomputer; hence the name *computer numerical control* (CNC). The program that controls the machine can be changed to alter the sequence of instructions. When a new production job is scheduled to be produced on the machine, the program is rewritten for the new job. NC had its origins in the machine tool industry. The first NC machine tool was demonstrated in 1952. Computerized versions of NC were developed during the late 1960s by connecting mainframe computers of the period to multiple machine tools. These systems were referred to by the name *direct numerical control* (abbreviated DNC), because the computer was directly interfaced with the machine control unit (a hard-wired controller) of each machine tool in the DNC system. The first CNC machines, in which one computer was used as the controller for only one machine tool, date from the 1970s, with microcomputers being used starting in the mid-1980s. Today, CNC machines are often connected to larger plant computers in *distributed numerical control* systems (also called DNC).

In addition to machine tool applications, many other uses have been developed for NC positioning control. Table 14.6.4 presents a list of the important applications of numerical control. Not all of these systems are called numerical control, but they are all based on NC concepts and principles.

Position Control in CNC

The common operating feature of these applications, machine tool and other, is position control of a processing element, such as a cutting tool, relative to an object being processed, such as the workpart being machined. Accordingly, a requirement for NC is that it must have a coordinate system by which the relative position of the "tool" can be defined with respect to the machine table on which the "work" is clamped. The coordinate system commonly used in most NC applications is shown in Fig. 14.6.14. It is based on the Cartesian coordinate system (x-, y-, and z-axes), with rotation (a-, b-, c-axes) defined about these linear axes. Not all six axes are used in every system. Some processes require control of only two axes; for example, a CNC sheet metal punch press. Other systems control five or six axes, an example being an *industrial robot,* whose coordinate system may be different than the Cartesian system, depending on the anatomy of the robot. It might be argued that an industrial robot goes beyond our definition of numerical control because its controls enable it to do more than merely position its manipulator. However, in terms of its position control capabilities, it operates as a numerical control system. Other CNC systems are also capable of more than just position control; an example is the tool-changing capability of a machining center.

It should be mentioned that in the positioning of the tool relative to the work, it is not only the tool that might be moved in absolute space. To achieve relative positioning, either the tool or the machine table can be moved, depending on the mechanical design of the system. In many NC systems, it is the table that is moved in relation to a fixed tool, in order to accomplish positioning.

TABLE 14.6.4 Applications of Numerical Control and Similar Positioning Systems

Machine tool applications	
NC milling machines	Milling and related operations
NC drill presses	Hole-drilling and related operations
NC turning machines	Turning and related operations
NC machining centers	Milling, drilling, automatic tool changing, automatic workpart positioning to present more than one surface to the cutting tool, and other functions
NC grinding machines	Grinding processes
NC pressworking	Sheetmetal punching, some bending
NC tube bending	Bending of tube stock, as for bicycle frames
NC Wire EDM	Electric discharge machining using a wire as the electrode to cut a thin kerf in plate metal
NC flame cutting	Torch-cutting of flat plates and sheets. Related processes include laser cutting, electron beam cutting, and plasma arc cutting

Other applications	
Electric wire wrap	Back-pin wiring of electrical boards
Coordinate measuring machine (CMM)	Measuring dimensions of mechanical parts in inspection
X-Y plotter	X-Y control of pen for plotting on paper
Drafting machine	Similar to X-Y plotter, for drafting
Component insertion machine	Position and insert parts on flat plane, such as printed circuit board
Industrial robot	Positioning of mechanical manipulator

There are differences in the level of control exerted over the relative position of the tool in a NC system. Two categories can be defined: (1) *point-to-point,* and (2) *continuous path.* In point-to-point control, the objective of the control system is to move the tool to a position defined in the coordinate system, without regard to the path taken to achieve the position. Once the tool reaches the desired position, some operation is performed at that location; for example, a hole is drilled, or a spot weld is made. In continuous path systems, called *contouring* systems in machining terminology, the path taken by the tool is controlled in real time. That is, the relative position of the tool is continuously controlled to achieve a desired motion trajectory. To accomplish this level of control, each axis must be controlled in terms of both position and velocity, and its movement must be coordinated with the movements of all other axes in the system. Continuous-path NC systems permit the tool to follow mathematically defined paths, such as straight lines, circles, ellipses, and other complex curved shapes such as those found in the design of airfoils and automobile car bodies.

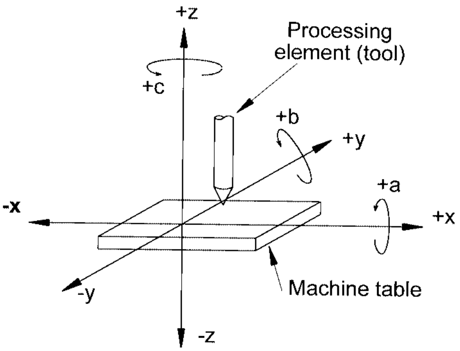

FIGURE 14.6.14 Coordinate system used for most numerical control applications.

Computer-Assisted Part Programming

The digital computer was applied in numerical control applications almost from the beginning of the technology, but not as the control unit in the NC system. The application was for *NC part programming,* which is concerned with planning and coding the sequence of programming steps to be performed on the numerical control machine tool. In the late 1950s and early 1960s, the APT part programming language was developed (APT stands for Automatically Programmed Tooling). This language, still used today, permits a person, called a *part programmer,* to define the geometry of the workpart and then specify the tool path required to machine the finished part, using English-like statements. The program is then entered into the computer, which performs the necessary calculations to generate a tool path code that can be interpreted by the machine tool controller. When APT was introduced (and for many years after), the medium used to input the program into the controller was punched tape—one-inch-wide paper tape with punched holes coded to represent the tool path commands. The controller, therefore, required a punched tape reader in order to read the contents of the tape.

APT has been largely replaced in many installations by enhanced versions of APT—languages based either directly on APT or on APT concepts. And the punched tape has been replaced by more modern digital storage media. In addition, *Computer-Aided Design* and *Computer-Aided Manufacturing* (CAD/CAM) which began rapid commercial development in the 1970s, were also based on APT concepts. Modern CAD/CAM systems, equipped with advanced software, are capable of performing many of the NC part programming functions automatically, thus providing valuable savings in part programmer time.

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BIOGRAPHY

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CHAPTER 14.7

PACKAGING EQUIPMENT AND METHODS

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The term *packaging* includes three kinds of activities: *item packaging, interior packaging,* and *exterior packaging.* The function of each is to protect the value and condition of the packaged commodity during transport, handling, and storage, and also to promote the efficiency of the transportation, storage, and cargo handling functions. When considering techniques of packaging, it is necessary to examine the overall situation in which product distribution takes place.

In this chapter, the current situation surrounding distribution and packaging will be considered, with particular reference to environmental issues such as the growing movement toward elimination of excess packaging, and recycling of used packaging material. The decision-making process regarding the introduction of packaging equipment is examined, including the trade-offs that must be made (for example, between perfect product protection and economy), the relationship to the production and cargo handling processes, and environmental considerations. Recent types of packaging equipment are reviewed and trends are discussed. Finally, such subjects as packaging material, packaging forms, and automation of the packaging process are also reviewed.

THE RELATIONSHIP BETWEEN PACKAGING AND DISTRIBUTION

The field of product distribution has recently been impacted by many trends, such as an increase in the variety of products handled, more frequent deliveries, an increase in the variety of packaging methods used, pressure to reduce inventories, and demands for shorter lead times. The result is that a variety of losses are occurring at each stage in the distribution process—procurement/production/sales. In many cases these losses are greatly influenced by the quality and effectiveness of the packaging specifications. For example, inappropriate packaging specifications often result in degradation of product quality, increases in product handling labor-hours, and worsened storage efficiency, all of which contribute to an increase in the cost burden to companies. In addition, the lack of people willing to work in the physical distribution business and the necessity of taking measures for environmental protection are well-known problems. For the foregoing reasons, packaging problems are becoming more and more critical to most companies.

Responding to the Need for Improved Efficiency and Greater Labor Savings

Today there is a strong demand for equipment and systems that make the packaging function more efficient and easier to do. This demand is in part a response to trends such as an increase in product varieties and decrease in lot size, greater frequency of shipments, rapid changes in the types of products and sheer volume of materials moving into the market, and demand for shorter delivery times. This demand also results from fundamental and structural changes in the product distribution system, including the current shortage of labor in the field of distribution and changes in people's attitudes toward work.

In the past, the main requirement placed on packaging equipment was to achieve high speed on the packaging lines, including shortening of the time for changeover between different products. Recently, however, dealing with environmental issues has become a high-priority subject for management. Likewise, emphasis has been placed on the labor-saving role of packaging equipment, in the sense of making the workplace safer and more comfortable by, for example, reducing noise levels. Other features required of packaging equipment are compactness, high reliability, and ease of maintenance.

In the pursuit of greater efficiency and labor savings, the trend toward standardization and qualification (ISO registration, etc.) of integrated distribution systems is one factor whose impact on future trends cannot be ignored. To realize greater efficiency and labor savings, not only in packaging, but in the entire distribution system, consistent palletization systems must be implemented. Achieving this advance is an essential element in building an integrated distribution system that will function efficiently, regardless of what transport means is used. For that purpose it is necessary to promote standardization and qualification of distribution equipment which recognizes the mutual interrelationship of such equipment, even bridging different companies. To implement this, the following types of standards must be adopted among all companies concerned:

1. Standards relating to unit load systems
2. Standards for distribution-related facilities and automation equipment
3. Standards for information systems

Based on such standards, a review of the standardization of pallet dimensions, corresponding unit load dimensions, and packaging configurations should be done. In conforming to this standardization program, the packaging system also must be thoroughly harmonized to the total distribution system.

Responding to Environmental Protection Programs

In industrially developed nations, as part of environmental protection plans, aggressive government ordinances have been instituted that aim at reducing the quantity of packaging materials used and the volume of waste material generated. This movement has strong popular support and is intended to correct the problem of excessive use of packaging materials, sometimes called *overpackaging,* and the burden of disposing of used (waste) packaging materials. Recently, the problem of disposal/treatment of waste has become very important, and it will be a critical issue in all considerations of packaging in the future.

Currently, the recognition of ISO 14000 that "used packaging material is not waste but a precious resource, and it must be reused or recycled" is becoming the world standard, and specifications that make packaging easy to reuse, recycle, or dispose of are being sought. The relevant ISO 14000 regulations are as follows.

1. *Purpose.* Limit packaging to the amount that is directly needed for protection of the contents and for safe product shipping, and, if it is technically possible and does not result in undue hardship, it should be reused. When it cannot be reused, it should be recycled.

2. *Scope of applicability:*
   - Packaging material manufacturers
   - Manufacturers of other packaging products
   - Distributors
   - Mail order operators

3. *Duty to reclaim packaging material.* It is mandatory for distributors and manufacturers of packaging products to reclaim packaging materials after use and then reuse them. When reuse in its existing form is not possible, the material must be converted to raw material and then reused as an ingredient. However, in cases where the consumer demands that the product be handed over still packed in all its packaging material, this duty is exempted.

4. Packaging material that can be reused or recycled must not be incinerated or thrown away.

5. Manufacturers also have a duty to reclaim decorative packaging material and end-user packaging materials.

Looking at regulations that have been instituted by other countries, the most severe one among industrially developed nations is the German "Ordinance for eliminating packaging waste," or as it is popularly called, the "German waste reduction law." It requires that every company be responsible for reclaiming and recycling all of the packaging material it generates in the course of its business activities. The scope of the law extends to waste of all sorts, including packaging materials for shipment, secondary packaging materials, junk cars, and electrical devices (electrical equipment, computers, toys, etc.).

Computerization

Just as microcomputers have been widely introduced into other kinds of industrial equipment, they have found application in packaging-related equipment. In fact, computer control has played an important role in enabling compactness and high functionality to be achieved at the same time. In integrating and systematizing a unified product flow—from production, through packaging, to distribution—creation of a distributed network, using PCs or workstations, results in many benefits. Those include greatly increasing the functionality of the total system, and supporting the creation of flexible, high-speed, low-cost systems. Computerization of packaging systems has thus become an important trend.

CONDITIONS THAT PACKAGING SHOULD SATISFY

Before considering packaging equipment, one must understand the conditions necessary for effective packaging.

The essential conditions for an effective packaging system are summarized in the following four points. When designing packaging or improving existing packaging, the distribution process of the product under consideration must be investigated in detail, and the packaging must be examined to determine if it satisfies these four requirements. Such examination of the distribution process is done primarily by focusing on three stages: in-company, first-level customer, end user.

1. *Balance between protection and economy.* At each stage of the distribution process, packaging must be able to fulfill the function of product protection most economically. First, packaging must be examined as to whether it protects the product under the expected material handling conditions (operators and equipment) and transport conditions (truck, railroad, ship, or air) in the distribution process. Packaging must protect the product from any danger of damage, degradation, or contamination. In particular, packaging must be designed and accomplished to suit the actual conditions expected in distribution, so that degradation of product value or deterioration of product condition due to environmental factors—such as vibration or shock, pressure, water, extreme temperature, and humidity—can be avoided.

To achieve the function of product protection most economically, it is necessary to consider whether the thickness, configuration, and material characteristics of the packaging material used are reasonable. For example, one must study whether the packaging material is of unnecessarily high quality, resulting in too high a price, or whether it is excessively thick or has an extreme configuration that increases the amount of material used.

2. *Efficiency.* It is necessary to examine whether, in any step of the distribution process, there is the danger that packaging will generate losses in handling efficiency, transportation efficiency, or storage efficiency, which in turn can result in increased distribution costs.

Looking first at the handling aspect, the connection with the manufacturing process must be smooth. In particular, there can be no negative impact on work efficiency. To ensure this, balancing must be done between the capacity of the manufacturing process and that of the packaging process. If an imbalance occurs, several kinds of losses can result:

- Stoppages of the manufacturing process
- Accumulation of work in process between the manufacturing process and packaging process
- Waiting time in the packaging process (equipment operating time loss, labor time loss)

The imbalances that cause such losses must be avoided.

Regarding the transportation aspect, in the case of truck shipment, for example, we seek to avoid dead time losses and loading volume losses caused by poor stowage or problems with loading and unloading. These losses can be avoided by examining the mutual coordination of three sizes: packaging size, pallet/container size, and the storage size of transportation facilities. Lack of conformity of these three sizes causes the utilization rate and loading efficiency of transportation facilities to fall, and as a result, excessive capacity of the transportation facilities and equipment must be deployed and total transportation costs become unnecessarily high.

Considering the storage aspect, losses as to storage area usage and height usage must be avoided. Again, these losses can be avoided by examining the mutual coordination of the three sizes, including packaging size, pallet/container size, and the size of storage facilities such as racks. Lack of conformity of these three sizes results in decreases in surface area usage efficiency and height usage efficiency on pallets, containers, and racks. As a result, excessive storage capacity must be provided and storage costs increase, just as in the case of the transportation aspect. As part of the storage aspect of packaging issues, effort must be spent examining the strength of packaging. It must be understood that if packaging strength is inadequate, the economic benefits of high stacking cannot be obtained, and storage efficiency drops.

3. *Convenience of handling as cargo.* Packaging must facilitate optimal handling of products as cargo (i.e., when products are packed in volume into carriers such as trucks and or ships and transported long distances).

Convenience of handling means that, for all the operators involved in handling the products as they pass through the distribution system as cargo or freight, physical handling must be easy, and the necessary instructions must be easy to understand. In particular, packaging specifications must provide that:

- Storage and handling are easy.
- The identifying description of the product is easy to understand.
- The top and bottom of the package are easy to distinguish.

When not enough care and attention are given to the issue of handling products as freight, mistakes by operators can occur, and wrong product deliveries or wrong delivery amounts will result. Finally, attention must be given to ease of unpackaging by the receiver and ease of packing material disposal by the end user.

4. *Public concerns.* Packaging must be responsive to prevailing social concerns, such as the elimination of excessive packaging and recycling of packaging materials.

As previously mentioned, responding to environmental issues is becoming a high-priority subject in the fields of packaging and distribution. First, excess packaging is to be eliminated by striving for the minimum amount of packaging that is viable. Moreover, as much as possible, packaging which can be reused or recycled should be sought and even if these goals are technically impossible, at a minimum packaging material which can be readily incinerated or disposed of in landfills should be selected.

Such a policy may already be considered part of a company's social responsibility and, considering the surge in environmental consciousness among people in general, it may be also be considered essential from the standpoint of marketing and public relations. Furthermore, even from the viewpoint of economy, cutting down on the amount of packaging material used certainly contributes to cost reduction. Even considering post-processing, such as recycling, although there may be a temporary cost increase, once the system is functioning, it will prove to be economically justifiable. For these reasons, packaging systems today must be designed based on such concepts.

VARIETIES OF PACKAGING EQUIPMENT AND CURRENT TRENDS

Varieties of Packaging Equipment

Packaging equipment can be classified into three categories: (1) machines for item packaging/internal packaging with the purpose of packing the product itself, (2) machines for exterior packaging and packaging for shipment, and (3) auxiliary packaging equipment.

1. *Machines for item packaging/internal packaging.* First, for the steps prior to actual packaging, there are product weighing machines and product filling machines. Then, in the packaging stage, there are bottling machines, canning machinery, and bagging machines, plus sealing machines for each of these. Among bagging machines, in many cases the bag-making equipment is combined with the bagging machine in a single unit. For each packaging method, there are compressive packaging machines which pack while reducing the size of the contents and vacuum packaging machines designed to better maintain product quality. Finally, there are labeling machines, which put identifying labels (often bar-coded) on product packages, and cartoning machines that pack individually wrapped products into cartons.
2. *Machines for exterior packaging and shipping packaging.* Following the typical process sequence, there are machines (*boxers* and *casers*) that make product boxes or cases. Next there are box-loading and case-loading machines, which load the box (or case) with product (including individually wrapped products or products with other internal packaging), and sealing or taping machines that close and seal the lid of the box (or case). Finally, there are strapping machines and tying machines to stabilize the product in the case.
3. *Auxiliary packaging equipment.* This category is mainly comprised of palletizers that automatically load products onto pallets, and slitters that cut sheets of packaging material to the desired length.
4. *Specific equipment types*
   The following list provides a summary of the major types of packaging equipment:
   A. Item packaging/internal packaging machines. Sample application: Individual packaging in the form of carton packaging (including cases where cartons are filled with liquids or other nonsolid materials).
      i. Package-making machines
         a. Film- or sheet-making equipment
         b. Drawn-film manufacturing equipment

    - ***c.*** Nonoriented film manufacturing equipment
    - ***d.*** Sheet manufacturing equipment
    - ***e.*** Automatic thickness-control equipment
    - ***f.*** Fully automated high-speed continuous vacuum molding equipment
    - ***g.*** Vacuum molding equipment
    - ***h.*** Pressure molding equipment
    - ***i.*** Metal casting equipment
    - ***j.*** Laminating equipment
    - ***k.*** Plastic reclamation equipment
    - ***l.*** Automatic trimming machines
    - ***m.*** Three-direction high-speed continuous bending machines
    - ***n.*** Multilayer sheet manufacturing apparatus
  - **ii.** Film sheet fabricating machines
    - ***a.*** Rolling machine for making small rolls, with built-in inspection unit
    - ***b.*** General-purpose slitter (for cutting large rolls of flexible package film)
    - ***c.*** Fully automated film-wrap packaging systems (in-line system which integrates automated equipment for taking up the molded web, wrapping the film continuously while slitting it to a fixed width as needed, and automatically cutting it)
    - ***d.*** Roll-type automatic packaging machine (for use with converted paper or plastic film)
    - ***e.*** Various adhesive tape slitters
    - ***f.*** Automatic combination bag-making and packaging machine (rolling film off tube>>automatic bag-making>>bag inspection>>automatic premeasuring of product weight or volume>>automatic product loading>>sealing and cutting>>transfer of product sealed in bags>>disposal of trimmings)
    - ***g.*** Automatic winding/automatic exterior-wrapping packaging machine
    - ***h.*** Defective-packaging removal equipment
    - ***i.*** Microgravure coater (for film and paper)
    - ***j.*** Coating/dry laminator (aluminum foil, copper foil, various films, paper)
  - **iii.** Bag-making machine
    - ***a.*** Fully automated high-output bag-making machine
  - **iv.** Container-forming machines (1) weighing machines for packaging, (2) filling/loading machines, (3) bottling machines, (4) canning machinery, (5) bag forming/filling machines, (6) container forming/filling machines, (7) labeling machines, (8) carton filling machines, (9) over-wrapping machines, (10) sealing machines, (11) packaging machines incorporating contents compressing feature, (12) vacuum packaging machines, (13) die-cutting machines, (14) cup/tube printer
- *B.* Machines for exterior packaging and packaging for shipment (1) case-filling machines, (2) case-sealing machines, (3) taping machines, (4) strapping machines, (5) string-type binding machines, (6) case-opening machines, etc.

  Sample application: Adding strapping to a cardboard carton or wrapping it in plastic film for ease of handling and preventing damage in transport

Development of Integrated Systematization and Automation

Recently, with the surge in requirements for efficiency and labor savings previously mentioned, there is strong trend toward mechanization to achieve integrated packaging systems, instead of introducing individual machines and attempting to link them. Also, the trend toward semiautomation or even full automation remains strong.

As an example, let us look at the case of a packaging automation system that uses sheets of plastic film. First, by introducing film roll-out machines with built-in automatic inspection units, it is possible to detect and eliminate errors in the use of film beforehand, and the labor required for the inspection process can be reduced. Also, by introducing a general-purpose slitter, which makes it easy to respond to changes in film size or the characteristics of film material flexibly and with "one touch," a drastic reduction of setup or changeover time was realized.

In the case of automatic bag-making packaging machines, fully automated equipment is now being introduced that performs the total process (i.e., from rolling out preslitted film, through the steps of automatic bag-making, bag inspection, automatic product premeasurement, automatic product loading, sealing and cutting, transfer of product sealed in bags, to the final step of disposal of trimmings).

CHECKLIST FOR PACKAGING ADEQUACY

When considering packaging approaches for effectiveness, the points that must be examined are packaging material, packaging configuration, automation of supply of packaging material, transportation factors, and conditions at the receiver. Specific points to be checked are described in the following sections.

Points to Be Considered in Packaging Design

1. *Is the protection of contents adequate?* In regard to packaging material and packaging techniques, it is essential to be diligent in gathering information, not only about materials and methods currently used, but also about new materials and new techniques. The characteristics of each of them must be continually evaluated. Among important types of packaging material, such as corrugated cardboard, wood for box frames, wooden boxes, and plastics, changes and improvements are occurring continuously. Looking at corrugated cardboard, for example, it is far from a single commodity; recently new forms with new functionality have come into the market and their applicability must be continually monitored. When the main objective is protection of the product, special-function corrugated cardboard should be used, such as:
   - High-strength cardboard for increasing the protection of the product
   - Nonslip cardboard for preventing load shifting in transport
   - Freshness-protecting cardboard for severe environment conditions (or long transport times) in the distribution process
   - Cold-maintaining cardboard for controlling temperature in the desired range
   - Rust-preventing cardboard for environments where there is the danger of rust

   When considering such materials, it is important to seek a method that not only enhances the protective function, but also permits cost reduction. This ambitious strategy should be kept in mind when examining the rest of the points (protection factor).
2. *Is it convenient for handling?* (ease of handling)
3. *Does the packaging system lend itself to automation of the packaging operations?* If not, can the human operations be done easily? (ease of packaging work)
4. *Can unpackaging and disposal of packaging materials be done easily?* (convenience factor)
5. *Is the necessary information clearly indicated?* This includes name of product, amount, weight, destination, opening/unpackaging method, directions as to handling, and so forth. (information display)
6. *Are there any problems with transport or storage?* (transport efficiency)
7. *Is the cost acceptable?* (economy factor)
8. *Has every effort at reducing containers and other packaging material been made?* (waste reduction)

9. *Can the packaging material be reused?* (reuse factor)
10. *Can the packaging material be recycled?* (recycling factor)
11. *Is the packaging material easy to incinerate?* (incineration factor)
12. *Can the packaging material be disposed of in landfills?* (ease of disposal)

Checklist for Improving the Efficiency of Packaging

To undertake improvement of existing packaging systems, a thorough investigation should be made according to the following points, while bearing in mind the context of packaging system design the basic issues previously described.

1. *Change of packaging material or quality of material.* Examine to determine whether there are any problems with the strength of the packaging material or the protection it provides against temperature, humidity, and so forth. Check whether the quality of material is excessive, or if there are new alternative materials with higher functionality and lower cost.
2. *Change of specifications as to configuration or dimensions.* Examine whether inappropriate packaging configuration or packaging dimension may be causing a decrease in the efficiency of handling packages as freight, in storage efficiency, or in transport efficiency.
3. *Increase in quantities or sizes.* At every stage, from the procurement process to the final stage of product distribution, examine from every perspective whether there are opportunities to benefit from economies of scale in every situation. This may involve increasing the number of units in a package, the number of packages on a pallet or in a container, the unit size for movement, or the unit size for transportation.
4. *Concentration or compacting.* Examine whether economies of concentration or compacting could be pursued within the packaging process for an individual product, in packaging processes which extend across a variety of products, in packaging processes at other factories, or in other processes occurring in the distribution chain.
5. *Systemization/modularization.* From every viewpoint (packaging specifications, equipment, process, facilities, and even the distribution system), examine whether systemization/modularization could be introduced to better satisfy the points previously listed.
6. *Standardization.* Throughout the distribution process (including packaging specifications which extend across various products in a company and packaging specifications of interrelated companies), examine if economic savings and improved ratios (such as number of products per container) can be achieved through standardization.

An Example of Improvement of Packaging Efficiency

As an example of a recent improvement in packaging design, we present here the case of improvement through "pallet stretch" packaging.

First, the method of prestretch, in which the steps of stretching the film and wrapping it onto a pallet of cartons are done separately, was introduced. This enabled the film to be stretched to three or four times its normal length, resulting in reduction of the amount of film used by 66 to 75 percent, and achieving an important savings of resources. In addition, the trash generated was reduced by 25 to 33 percent, so that the goal of reduction of industrial waste was also achieved. Furthermore, by improving the packaging machine that wrapped the extended film, it was possible to achieve uniform tension across the whole palletized freight, and the level of protection in transportation was also improved.

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BIOGRAPHY

Daisaku Ohta graduated from Tamagawa University, Department of Management Engineering, in 1969. After a short period in industry, he joined JMA Consultants, Inc. (Tokyo) in 1971. He became a senior consultant in 1990, was promoted to Director of the Logistics Innovation Department in 1995, and has been a director of the company since 1997. One of the major themes in his consulting work has been the reconfiguration of logistic processes to optimize them from the consumer's standpoint. He assists companies in competing through more effective logistics (in terms of service and cost) even when their products do not offer a competitive advantage. Mr. Ohta is coauthor of *A Practical Handbook for Management* (in Japanese) and is the author of several texts for correspondence courses.

CHAPTER 14.8

AUTOMATION WITH ROBOTS

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The aim of this chapter is to help the industrial engineer in the selection, installation, and operation of robot systems in industry. Industrial robots operate usually on the shop floor, in a *structured* environment. Such an environment can be structured by engineers to make the robotic application more productive, safe, and error-free. Therefore, the emphasis of this chapter is on the characteristics and limitations of the industrial robot, discussing the best ways to use it and make it fit for the task. Robot basic configurations, control systems, end-effectors, feeders, fixtures, sensors, and programming systems are covered in detail. A short case study exploring the automation of a manual assembly/welding and packing operations by a robotic cell is also included. The last section of this chapter gives a short overview and classification of mobile robots, and discusses the potential for their use on the manufacturing shop floor in the future.

BACKGROUND

The installation and operation of a robotic manufacturing system frequently proves to be a much more expensive venture than initially planned or imagined. Robotic systems are expensive to purchase, install, and operate. Unrealistic expectations, based on misunderstandings of robot capabilities and limitations, may lead to errors in the robotic cell and application design. Such errors are very expensive and difficult to rectify once the robotic equipment is selected, purchased, and installed. Unfortunately, engineers and managers sometimes tend to blame the robot or the technology for the problems encountered during implementation. An example of such misconception can be found in the following account, quoted from a *Time* magazine article [1] analyzing the problems of the U.S. robot industry:

> Some of those who rushed to buy an expensive robotic system got less than they bargained for. At a Ford Motor plant in St. Louis, snags in 200 production-line robots delayed the 1986 introduction of the Aerostar minivan. Then the discovery that the same robots had been skipping many key welds led to the recall three months later of some 30,000 of the vehicles. In another disastrous episode, a Campbell Soup plant in Napoleon, Ohio, was outfitted with a $215,000 system designed to lift 50-lb cases of soup. But any time it encountered defective cases, the machine would drop them, causing thousands of dollars in damage. Eventually the robot was donated to a local university and replaced by three humans. Says Warren Helmer, the company's manager of engineering research and development: "Campbell's was ready for robots, but robots were not ready for Campbell's."

However, it was not the robot's fault that welds were misplaced or skipped, or defective cases were dropped. Careful and well-designed implementation, by engineers who are aware of the capabilities and limitations of the technology, could solve these problems. The *industrial* robot operates in a structured environment that is relatively well defined and can be engineered and modified for the best use of robotic technologies (in contrast with robots operating in unstructured environments such as space exploration missions, underwater missions, or nuclear disaster cleanup). The uncertainties that exist in a structured environment (such as defective soup cases) can be identified and anticipated, and handled by the correct implementation of sensors, feeders, fixtures, sorting procedures, and other techniques.

The operation of robots is also frequently less efficient and effective than expected. The main advantage of robots is their flexibility, which allows their implementation for manufacturing a variety of products in small and medium batch sizes. Flexibility is essential in modern manufacturing to respond to short product life cycles, varying demand, small production lots, and model changes. However, productivity is much easier to achieve in a dedicated mass production system, and few flexible systems are also highly productive. Hence, when designing automation by robots, it is important to analyze each task and define whether it needs and justifies the use of flexible automation. For some repetitive task elements, a simpler fixed automation, such as a pick-and-place device, indexing table, and/or parts feeder may provide a cheaper and more efficient solution. For other task elements with high variability the flexibility of the robot may not suffice, and a human operator with intelligence and ultimate flexibility may be the most effective solution.

Automation, whether fixed or flexible, can be easily justified for tasks with the 4-D characteristics: dangerous, dirty, difficult, and dull. Removing the human worker from such unfriendly and risky tasks may be sometimes required by OSHA regulations, and has the added benefit that robots and automatic machines perform with the same repeatability, reliability, and quality regardless of disturbing environmental factors.

In this chapter, we will focus on understanding how a successful implementation of robotic automation is designed and implemented. We will start by analyzing the different elements of a robotic system, and understand how they either limit or enhance the flexibility in an implementation. Examples of simple tasks will be used to illustrate these concepts. We will review the key elements of a robotic system to understand how they affect design decisions related to robot selection, placement and programming, and the design of the task environment (robotic cell) including such elements as grippers, fixtures, feeders, and sensors. Finally, a complete case study of an industrial application will be presented to illustrate the design and implementation procedure of a robotic automation solution for a manufacturing problem.

THE FLEXIBILITY AND LIMITS OF ROBOTIC AUTOMATION SYSTEMS

Is the Task Fit for Robotic Automation?

The Robotic Industries Association (RIA) defines a robot as "a re-programmable multifunctional manipulator designed to move material, parts, tools, or other specialized devices through variable programmed motions for the performance of a variety of tasks." It is easy to be misled by this definition in interpreting the flexibility of robots. A simplistic interpretation of the robot definition may lead one to believe that a single robot is multifunctional and flexible enough to move different materials, various parts, and specialized devices such as welding guns, spray-painting guns, drills, and deburring tools through all the needed motions of a given task. Now it is only a step from attempting an application in which a single robot would assemble a device, weld it, paint it, and pack it for shipment. But the current robotic technology will not effectively support such an implementation. While a single human operator is flexible enough to assemble, weld, paint, and pack a device, a robotic system is much more specialized, less flexible, and limited mainly in the elements we may call the *mechanical interface.* This mechanical interface includes the configuration of the robot arm, its degrees of freedom, specialized and different grippers and tools needed for each operation, and specifically designed fixtures and feeders. The mechanical interface limits the flexibility of a robot, and enables it to deal only with specific operations of the entire task (such as assembly *or* welding *or* painting, etc.). Similarly, the mechanical constraints of current technology of grippers, fixtures, and feeders limit the robotic system to handle a relatively small family of part and material shapes. The element that helps to enhance robot flexibility is what we may call the *logical interface* comprised of sensors (both simple and complex, such as vision systems or tracking devices) integrated with the help of robot control and programming software. Correct robotic system implementation can be achieved only by fully understanding the limitations and constraints imposed by the elements of the mechanical interface and fully exploiting the flexibility granted by the logical interface.

Indeed, when we take a closer look at the reality of robot implementations in industry, we find little exploitation of the flexibility promised by the definition of a robot as a "reprogrammable multi-functional manipulator." Most robots are employed in a single, repetitive task, such as spot welding identical car bodies, painting along an automotive assembly line, or loading and unloading parts into manufacturing equipment. Robotic assembly is typically set up as an assembly line, with robots that each specialize in an assembly of a single part of a specific product, manufactured in large quantities in a mass-production type of environment.

To further illustrate the limitations to the flexibility of currently available industrial robots and their ability to perform a variety of tasks due to the mechanical interface—along with the potential to overcome some of the limitations of the logical interface—we examine in detail the implementation of robots in arc-welding operations. The arc-welding application itself can benefit considerably from the use of robots. The work environment is hostile and potentially dangerous to human workers. Both the welders and people working around the welding area are exposed to a variety of hazards such as toxic fumes, eye damage, electrical shock, and burns. High-positioning accuracy and consistent welding speeds are required for production of quality welds. These requirements demand a high degree of skill and effort from a human operator. A robot can perform the welding task with high repetitive accuracy and remove the human operator from the unhealthy and risky environment.

However, in spite of being the dangerous, dirty, difficult, and dull type of task for which robots were meant, introduction of robots into arc welding has been relatively slow. The main reason for this situation is not technological, but economical. The major portion of arc-welded products is manufactured in small and medium batch sizes, for which the expensive setup related to the need of special fixtures and robot reprogramming cannot be justified. A human worker can simply clamp the welded part, and then weld it in any position by using his or her (shielded) eyes for guidance. For a robotic welding system, very accurate and consistent part positioning is needed. As a result, special and expensive fixtures must be designed and made for each welded part type. In addition, a human worker can easily handle the part, clamp it, weld it, and unload it. In the robotic application, the robot can only hold the welding gun (changing tools for this application is neither practical nor efficient). Hence, the human operator (or a different robot) will be needed to load and unload parts.

Some savings in the setup involved with the need to use expensive fixtures for each welded part type can be achieved in some instances by identifying families of similar parts and designing a single adjustable fixture for each part family. As a result, the setup cost related to tooling is reduced, increasing the probability that smaller lot sizes would be acceptable and cost-effective in the robotic application. One such analysis of the savings in robotic arc welding was performed by Knott, Bidanda, and Pennebaker [2]. The analysis used a single fixture policy and an appropriate part type mix, such that the robot welds one part type, while another part type is loaded into a fixture at the loading station. The analysis showed that due to the savings in tooling costs, the probability of the acceptance of a candidate job for robotic welding increased by a factor between 1.6 and 2.0, when based on return on investment (ROI) criteria.

However, the real promise to overcome the limitations posed by the mechanical interface in robotic arc welding lies in better utilization of the logical interface: sensors, adaptive control, and programming tools. Research, which leads in this direction, includes development work to provide expert systems as an aid for design of weld parameters [3], and the use of sensors for joint tracking and adaptive control of the welding path and parameters [4,5]. Integration of such work with a global welding task planning system [6,7] would result in increased flexibility of an automated robotic arc welding.

Robot Basic Configurations and Degrees of Freedom

The step that follows the initial analysis of a task at hand, and identification of the task elements for which flexible (robotic) automation is appropriate, is the selection of the robotic arm best suited for each task element. The robot mechanical arm basic kinematic configuration, and its number of degrees of freedom, is a major factor of the mechanical interface, which determines the flexibility and dexterity of the entire system.

Joints connect the links of a robot arm. In commonly used robotic mechanisms two types of joints, each with a single degree of freedom (DOF), are used: a prismatic joint (P), and a revolute joint (R) (see Fig. 14.8.1). The prismatic joint allows linear motion of one link relative to the other, along a single axis. The revolute joint allows a rotation of one link relative to the other, around a single axis.

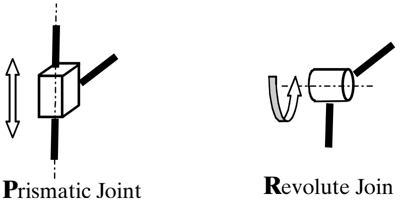

FIGURE 14.8.1 The joints used in a robot manipulator.

The first three degrees of freedom (three joints) in a robotic arm define the basic kinematic configuration of the arm. These first three degrees of freedom allow placement of the end-effector of the robot in a given point in space, but they do not suffice to define a required orientation in space. The required orientation can be achieved by using additional one to three revolute degrees of freedom.

The vast majority of commercially available robots have one of the following five basic configurations (letters in brackets denote the joints of the three first DOF):

- Cartesian coordinates (rectangular) configuration [PPP]
- Cylindrical configuration [RPP]
- Polar coordinates (spherical) configuration [RRP]
- Jointed-arm (articulated) configuration [RRR]
- Selective compliance assembly robot arm (SCARA) [RRP]

These five configurations are shown schematically in Fig. 14.8.2.

Each configuration has advantages and disadvantages that limit the scope and variety of applications fit for it. In machine loading and unloading applications, the ability of the robot to reach into narrow and deep openings without interference with the sides of the opening is important. The cylindrical configuration has a natural geometric advantage for such an appli-

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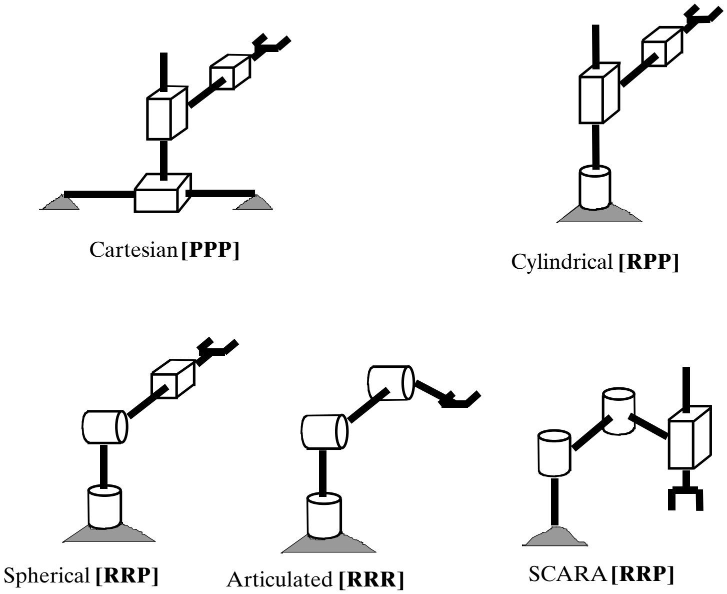

Cartesian **[PPP]**

Cylindrical **[RPP]**

Spherical **[RRP]**

Articulated **[RRR]**

SCARA **[RRP]**

FIGURE 14.8.2 The five basic configurations of a robot manipulator.

cation, while a jointed-arm robot would be completely inadequate for such a task. On the other hand, the jointed-arm configuration has the dexterity needed to reach above and around obstacles in a welding or painting task, an ability that is not available with the other configurations.

The SCARA configuration is specifically designed for vertical insertion and assembly tasks. It has a stiff and rigid structure in the vertical direction, which allows it to exert a high force during insertion and bear higher payloads. It also can use passive compliance in the horizontal plane, which makes assembly with tight tolerances possible. A large Cartesian coordinates gantry-type robot has the high rigidity required for carrying heavy loads, but may be unfit for other applications. In general, the payload that a given robot will be able to carry will be affected by its basic configuration much more than by its drive systems.

The extent and shape of the robot workspace is determined by its basic configuration, physical dimensions of the links, and the limits on motion around each of its joints. Most industrial robots are bolted to the floor in one predetermined location, although mobility can be increased in some applications by mounting the robot on a track or an overhead gantry. With this limited mobility of most industrial robots, the application and layout is planned around the robot workspace. If a cylindrical robot were selected to load parts into machines in a flexible manufacturing cell, the machines would be configured around the robot, within its work envelope. The flexibility of the robot would be limited within the machine-tending application to loading a variety of parts into the machines in the cell.

The basic configuration of a robot manipulator selected for a given task also defines the additional degrees of freedom that will be required to accomplish the task. The three additional degrees of freedom, which are needed to orient the end-effector of the robot (and with it the tool, part, or material carried by the robot) to any required orientation in space, are pitch, yaw, and roll. These degrees of freedom are illustrated in Fig. 14.8.3.

If a certain robot configuration is selected for a task, the number of orientation degrees of freedom required may vary. Hence, if we select a configuration that is capable of performing a task with a minimal number of degrees of freedom, the total cost of the manipulator can be

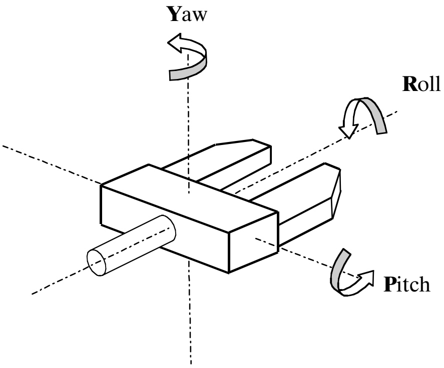

FIGURE 14.8.3 The orientation DOF of a robot manipulator.

reduced (each orientation degree of freedom requires a drive, and the additional control loops to control such drive).

To illustrate this concept, let us use a simple application that can be performed by any one of the five basic robot configurations. A robot is needed to load boxes into a machine. The parts arrive on a conveyor belt, which is 1 m high. The machine opening is 2 m high. When a batch of new boxes arrives in front of the robot, the conveyor stops, and the robot has to load all of them into the machine. The layout of the conveyor, machine, and planned robot location are shown in Fig. 14.8.4.

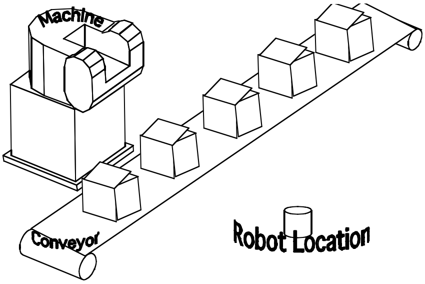

FIGURE 14.8.4 A layout of a simple machine-loading application.

If a Cartesian robot is selected for this application, it would need only the three primary DOF to complete the task. A cylindrical robot would need one additional DOF—a yaw—to adjust the gripper orientation when picking boxes that are not in front of the robot. The spherical and articulated robots would need two additional DOF—a pitch and a yaw—to correctly orient the gripper when picking boxes and placing them in the machine opening. And a SCARA robot would need one additional DOF—a roll—to orient the gripper according to the orientation of the boxes on the conveyor and the machine opening.

In a complex task with difficult-to-reach areas, where the robotic system needs high dexterity to achieve the required position and orientation of the end-effector (POSE), it is sometimes possible to solve the problem by adding external degrees of freedom that can move or rotate the part. For example, in a welding of round parts (pipes, cylinders, boilers, etc.), a positioning table that can rotate and tilt the part can be used to help the robot reach all required weld-seam locations at the proper orientation of the welding gun.

The Control System

Another major factor limiting the scope of applications in a given industrial robot is the control system of the robot. The two main types of control used in industrial robots are point-to-point (PTP) control and continuous path (CP) control.

Point-to-point controllers lack the computational ability to perform trajectory interpolation, such that the path and velocity of motion of the robot end-effector tool center point can be controlled. These PTP controllers, which are typically cheaper, can control the robot to reach a desired sequence of discrete points, and perform operations at these points, but do not control the path taken by the robot to get from one point to the next, nor the velocity along that path. Robots with point-to-point control are limited to applications such as machine loading and unloading, palletizing, and spot welding. In programming the robot, care must be taken to avoid collisions since the path between any two programmed points cannot be easily predicted by the operator. Continuous-path controlled robots are required for applications such as spray painting, grinding, deburring, or arc welding in which both the path and velocity of the tool must be closely controlled. Robotic assembly may also require continuous path control to successfully complete insertion operations. However, in carefully planned assembly applications, where only vertical insertion is used and compliant devices are employed, point-to-point control would suffice.

End-Effectors, Feeders, Fixtures, and Sensors

Even within a carefully defined application area robot flexibility is limited by the capabilities of its end-effector, the variety of tools that can be mounted on its wrist, and the need for feeders and fixtures as accessory devices helping the robot to locate parts.

Robot end-effectors are either grippers designed to allow the robot to pick up objects, or specialized tools designed to perform a certain process such as spot welding, arc welding, or deburring. Specialized tools and grippers can represent more than 10 percent of the robot cost, and their flexibility is low. In a manufacturing process that requires a specific tool and additional auxiliary equipment (such as in arc welding or spot welding), the robot will be typically limited to the single process defined by its tool. In certain other processes, such as deburring, grinding, or other metal-removal operations, a common interface for tool mounting can be designed, and a tool-changing rack with multiple tools can be used to increase the flexibility of the robotic application.

Gripper flexibility is also limited due to conflicting requirements for gripper design resulting from various part sizes and geometry, part material and surface, or temperature of the parts to be manipulated. If parts of different shapes and characteristics have to be handled in a manufacturing cell by a single robot, or assembled in a robotic assembly cell, a single gripper of simple design would not provide the flexibility required. A changeover system, similar to a tool-changing rack, can be used to replace the entire gripper or select different gripper fingers. Such systems are expensive, but they may be adequate for machine loading and unloading operations in which the robot can change tools during an otherwise idle time while waiting for a machine to complete its manufacturing cycle.

However, in assembly tasks, such tool-changing activity will cause a major increase in the cycle time required for assembly by the robot. This problem could be resolved by the design of a universal gripper, and research and development work in this area is still ongoing. One research direction is patterned after the human hand, which has the required versatility. The mechanical and control complexity of such a device resulted in most designs (such as the Stanford/JPL hand or the Hitachi Ltd. hand) being limited to three fingers. Another approach of passive adaptation to the form of the object grasped uses a conventional gripper in which elastic fingers can conform to the shape of the object, either by pneumatic pressure or by fixing packed granular powder around the part using magnetic forces or vacuum. The main problem with both designs is the difficulty in controlling the exact position and orientation of the grasped part.

Sensory capabilities of most industrial robots are relatively limited. Research in computer vision is still far removed from practical solutions to problems such as picking an item from a bin of unordered parts. Technologies for seam tracking, such as may be needed for robotic arc welding, are available but expensive. As a result, most robotic applications have to rely on consistent placing and location of the workpieces within the robot workspace. Part feeders can be used to deliver parts to the robot in a known position and orientation. Fixtures have to be designed to consistently locate parts so that a robotic job can be repeated without reprogramming and without expensive sensory devices. Both feeders and fixtures limit the flexibility of the robotic installation. Most feeders are designed to handle, deliver, and orient a single part, or a finite range of geometrically similar parts. Vibratory bowl-feeders are more versatile, and are capable of handling a larger variety of parts by mechanical changes and adjustments of the sorting and orienting tooling at the end of the bowl track. However, the specific tooling is expensive and requires considerable setup time for adjustment and change, limiting the flexibility to change over from one part to another for small production lots.

Recently, special programmable bowl-feeders have appeared, increasing the flexibility of feeding. One type, developed by Westinghouse, allows automatic adjustment of tooling under computer control, in order to accommodate different parts. Another, even more flexible programmable feeder, developed by Programmable Orienting Systems, Inc. (POSI), uses a matrix of photosensors coupled through a fiber-optics cable to a computer controller. The controller software is programmed to recognize whether a part in the required orientation is present at the end of the bowl-feeder track and reject any other parts back to the bowl by activating a stream of compressed air.

Fixtures present yet another roadblock to achievement of flexibility in robotic applications. Due to the stringent requirement for consistent and accurate part positioning in robotic applications, fixtures for applications such as robotic welding are much more expensive than fixtures for manual welding, which only need to hold the part in place. In addition, in certain applications, multiple fixtures or pallet fixtures are required so that the robot may work continuously while parts are loaded into a fixture in another station.

The limits to flexibility of robots within a certain application group, which are posed by the physical limitations of grippers, tooling, feeding devices, and fixtures, can be reduced by technological solutions and developments. However, the real promise for increased robot flexibility depends on better sensory capabilities for robots, coupled with more powerful and intelligent programming systems. Such systems would allow relaxation of some of the stringent positioning and orientation requirements, which make feeders and expensive fixtures a necessity in robotic applications.

Robot Programming Systems

A large number of robots used in industry today are still programmed by an on-line programming method. This method is known as teaching by showing or guiding. The robot is moved through a sequence of desired positions, either by moving the end-effector manually or by the use of a teach pendant. The joint coordinates corresponding to each position are recorded by the robot controller. The main advantage of this method is ease of use. Programming may be performed relatively easily by shop floor workers, and does not require special computer programming skills. This programming method is sufficient for a wide variety of repetitive tasks for long production runs, and when modifications to the preprogrammed sequence are not required. However, there are severe limitations to on-line programming when applied to more advanced, flexible manufacturing (mostly in low and medium batch production).

The main disadvantage of on-line programming is the limited ability to use sensory inputs as a guide for different program alternatives. When using most on-line teach-and-repeat programming methods, one cannot program sensory inputs and conditional branching, which is based on these inputs. In the most advanced on-line programming systems, such as the teach-pendant programming unit for the second generation of ASEA Industrial Robots, limited

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conditional branching based on sensory inputs is allowed [8]. Such advanced programming capabilities are not very common in the commercial on-line systems, and are a combination of the teaching-by-guiding method and a full robot-level programming language. Another disadvantage of on-line programming is that it has to be performed using the actual robot, an expense of time that could be otherwise used for actual production. Since in many robotic applications the robot is only a part of a larger manufacturing cell, on-line programming actually wastes the useful production time of several production resources. In addition, on-line generated programs can seldom be moved from the robot on which they were programmed to another robot, even if it is of the same type. These limitations increase the need for off-line robot programming systems. Such systems may offer additional advantages in programming tasks where computation rather than teaching is more effective (such as palletizing), and can benefit from integration of information about the task environment from a computer-aided design (CAD) system. Two main levels may be distinguished between the existing off-line programming methods: robot-level programming and task-level programming [9]. Robot-level programming combines three elements:

1. The capability of a general-purpose computer programming language
2. The ability to use sensors
3. The capability of specifying robot motions in terms of either world or tool-center-point (TCP) coordinates

The key advantage of robot-level programming is the ability to use input from external sensors, such as force or vision, to modify the robot motion. This allows for implementation of an adaptive, or actively compliant system. However, robot-level programming systems are much more difficult to program than on-line teach-by-guiding systems, and require considerable expertise in computer programming and in the design of sensor-based motion strategies.

Task-level programming systems attempt to simplify the robot off-line programming process by a user interface through which only a specification of the robot task goals and the relationships of objects in the robot environment is required. Such task-level specification is completely robot independent. It is not necessary to specify paths or positions that depend on robot geometry or kinematics. The task-level system uses a task-planning module, which converts a user specification of a task into a robot-level program. Complete geometric models of the robot and its task environment are required as input for the task planner. Task-level robot programming systems, while carrying the promise of robot independence and ease of programming, are still an area of research and development. However, several commercial systems for robot and robotic work cell simulation (such as RobCad, Silma, Deneb) exist, which enable the task-level programming and debugging of robotic applications in a virtual, CAD-based environment. These systems help the engineer also with the tasks of robotic cell design, robot selection, verification of robot reach, and of correct placement of the cell elements. The application design along with off-line programming and simulation of the robot task can all be done in a virtual CAD and simulation environment. Simulation models that accurately represent the proposed robot and cell geometry, and the robot kinematic and dynamic performance, are valuable tools for evaluating design alternatives, verifying feasibility, designing work cell layout, verifying robot programs, and evaluating cell performance.

CASE STUDY—PALBAM INDUSTRIES

Description of the Application

Our sample company, PalBam Industries, Inc., manufactures stainless steel plumbing joints and fixtures for the food and health industries. A typical product is shown in Fig. 14.8.5. The company manufactures about 60 different joint models, which weigh between 0.5 to 1.5 kg.

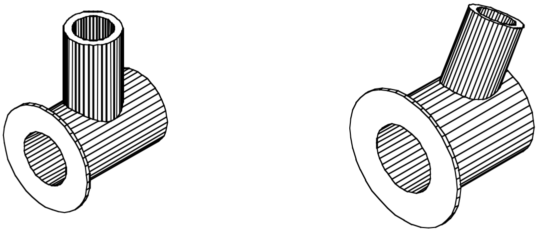

FIGURE 14.8.5 Typical stainless steel plumbing fixture.

Currently the company is considering replacing the manual assembly/welding and packing operations on the product by automated operations in a robotic cell. The assembly/welding operation requires high accuracy, and the company hopes to increase the quality and consistency of welds by using a robot. Workers' health and safety in the current manual method is also a cause for concern.

The manufacturing processes involved include initial assembly by a few spot welds to hold the parts together, followed by arc welding of the entire fixture. Following welding, the parts are removed from the welding table, inspected, and packed in cardboard boxes. The weight of a box with products is between 10 to 20 kg. The boxes are palletized on wooden pallets and removed to final goods storage by a forklift.

Method of Design of the Robotic Cell

It is not the intention of this section to provide a complete design solution for our case study problem. There are many good possible designs, and a detailed solution is left as a challenge for the reader. We will try to outline here a method for design, highlight main concern and problem areas, and provide direction, based on the discussion in the previous section.

The first step required is to define the need for robotics and automation by analyzing the different task elements in terms of the 4-D characteristics, required flexibility, and so on.

For PalBam, the following elements need to be scrutinized:

- *Assembly and spot welding of the fixture.* A worker can clamp the parts together, and then spot weld them. High accuracy is not required for this operation because it is for the seam arc welding that needs to be water tight. The job is relatively easy, and the occupational risk factor is relatively low. On the other hand, this task element is relatively difficult to automate. The fixturing of parts, assembling, and spot welding them may require quite elaborate fixtures and cannot be done by a single robot. So, while this task element presents a very challenging application for automation and robotics, it is doubtful that a solution to this challenging problem will be cost-effective.
- *Arc welding.* This task element justifies automation both to increase the quality and consistency of welds and to improve workers' health and safety. Robots are definitely justified due to the flexibility needed to weld the different fixture models. One concern is the need to design universal or flexible fixtures to hold consistently the different parts. The challenge here is to reduce the cost of such fixtures and try to avoid the need to change fixtures for different parts.
- *Unloading the welded fixtures and packing them in cardboard boxes.* This task element may justify automation mainly due to the monotonous (dull) nature of the job. Since different part sizes and part quantities are packed in each box, there is a well-defined flexibility in this task that may justify robotics.

- *Palletizing cardboard boxes on a wooden pallet.* This work element is both dull and difficult/dangerous (handling heavy boxes for prolonged times presents a risk of back injury). If boxes are of the same size, it is possible that a pick-and-place palletizing manipulator (fixed automation) could be a cost-effective solution.

Following this initial analysis, a detailed design is needed for each task element that was selected as a candidate for automation/robotics. For each such task, the following steps are required:

1. *Selection of a robot.* This step must consider the required work envelope, number of degrees of freedom (robot configuration as based on three primary DOF, and additional DOF required for the end-effector), motion accuracy and repeatability, payload, speed of motion, drive types, control type, method of programming, communication capabilities with the environment (number of input/output [I/O] ports for sensors and activation signals), and capability of access and motion between obstacles. Some of the commercial CAD robot simulation systems have large libraries of models of commercially available robots, and they can help considerably in evaluating different alternatives. When selecting a robot, the available programming methods should also be considered. For the PalBam case, a CAD-based off-line programming system capable of generating a weld-path program based on the fixture geometry is probably the ideal choice for the welding robot, due to the accuracy requirement and the large number of models made.
2. *Design of fixtures, feeders, sensors, and specific grippers and end-effectors.* This step will deal with questions such as, Is a seam-tracking system required for arc welding, or can this expenditure be avoided due to high consistency of the fixturing and handling process and part tolerances?
3. *Integrated design of the work cell.* This includes the design of material-handling devices, location of robots in the cell, and placement of sensors, feeders, safety fences, and the like. This step is also best designed using a commercial CAD robot simulation system.
4. *Implementation plan.* A detailed project planning of the installation, training, system testing and run-in, including detailed time and cost estimates, is needed. Simulation systems, project planning, and control software can assist in this step.
5. *Economic justification.* This step is similar to justification of any major project. Benefits of the proposed system should be quantified (savings due to quality improvements, productivity improvements, health care costs, etc.) and analyzed to justify investment using economic analysis. Several solution alternatives (such as fixed automation or manual labor versus robotics for certain task elements) are also analyzed in this step.

MOBILE ROBOTS

Why and Where Is Mobility Needed?

The main purpose of adding mobility to industrial robots is to expand the robot workspace. An industrial robot working in a large painting booth, welding large structural parts, or performing assembly operations on an automotive assembly line needs mobility to work in areas that are outside of the work envelope of the manipulator arm. Such simple mobility can be easily achieved in a structured industrial environment by mounting the robot manipulator on a track, and controlling the motion on the track. The required control is simple, accurate, and easily integrated with the standard robot controller and programming system.

Larger degree of mobility and added flexibility may be required on the manufacturing shop floor for material-handling applications. Raw materials and parts in process may need to be transported between various and changing locations, and in various quantities. In most industrial settings, this type of required handling and transportation flexibility is achieved by automated guided vehicle (AGV) systems. AGVs are battery-powered, automatically steered vehicles usually designed to follow a network of defined pathways (defined by a guiding wire or painted path on the floor). Most AGVs automatically load and unload unit loads. Autonomous mobile robotic systems, equipped with different sensors and manipulator arms, can potentially provide extended capabilities that AGVs currently do not possess. These capabilities include motion that is not restricted to predefined pathways, sophisticated obstacle avoidance, and ability to perform various tasks by using their manipulator arm(s). This can open a whole range of new service functions for mobile robot systems, such as surveillance, cleaning, and operation among freely moving humans.

While AGVs may be the method of choice for highly structured environments, autonomous mobile robots play an ever increasing role when the world becomes less predictable and more dynamic. Indeed, special-purpose and one-of-a-kind mobile robots are mostly used in unstructured environments—such as mobile robots for nuclear disaster cleanup, or underwater and space exploration. Mobile robots are also used for tasks in moderately unstructured environments, such as inspection and maintenance tasks in the nuclear, marine, offshore, chemical, petrochemical, and construction industries. Today, mobile robots are already becoming cost-effective (although not commonly used) at construction sites [10,11]. In the future, with further advances in the accuracy of navigation and motion systems, and in software and sensory capabilities, mobile robots may become cost-effective on the manufacturing shop floor.

How Mobile Robots Operate: Challenges and Research Issues

To be able to successfully perform their task, autonomous mobile robots must reach their target destination accurately and safely (without collision). In order to navigate, knowledge of the present position and path planning towards the target while avoiding obstacles are required. Such navigation is very difficult even in moderately unstructured environments due to several sources for uncertainty. This uncertainty is a result of sensory limitations, motion control limitations, and limitations in modeling the environment.

Sensors are limited by their resolution, and by the system ability to interpret or ignore noise factors in the environment, such as reflections, uneven lighting, and shadows. For example, ultrasonic sensors, which are very cheap and commonly used for mobile systems, are notorious for their poor resolution and specular reflections. Vision systems are sensitive to lighting conditions and have to infer correctly 3D information and distances from 2D imagery.

Motion control is mainly limited by the open control loop of mobile systems. The control system controls the amount of motion of the robot wheels or legs, but has no control over traction, uneven floor, or slippery surfaces. All these factors result in uncertainty about the current robot position and must be corrected by external sensors.

A CAD model of the environment is frequently used as the basis for navigation, path planning, and position recognition. Errors in such models are inevitable. They may have been inaccurate initially, the world may have changed since their creation, or they may be incomplete.

Autonomous navigation of mobile robots is a challenging task even if the environment uncertainties can be reduced. Autonomous navigation systems must apply obstacle avoidance algorithms simultaneously with the robot steering toward a given target. Global path planning algorithms [12] are used to plan the robot's path among the known obstacles, while local path planning is needed for real-time obstacle avoidance. Real-time obstacle avoidance is one of the key issues to successful applications of mobile robot systems. All mobile robots feature some kind of collision avoidance, ranging from primitive algorithms that detect an obstacle and stop the robot short of it in order to avoid a collision through sophisticated algorithms that enable the robot to detour obstacles [13–16]. The latter algorithms are much more complex since they involve not only the detection of an obstacle, but also some kind of quantitative measurements concerning the obstacle's dimensions. Once these have been determined, the obstacle avoidance algorithm needs to steer the robot around the obstacle and resume motion toward the original target.

Another challenging issue in development of mobile robots is the method of locomotion by which the robot moves. Mobility can be added using wheels, tracks, or legs (we discuss only land operating robots here; different propulsion and steering methods are used for air and sea systems, which are beyond the scope of this chapter). The choice of locomotion type depends mainly on the characteristics of terrain in which the robot will move. Wheels are most useful in terrain with few obstacles. Wheel size and suspension is designed based on the terrain roughness (maximum height of obstacles to get over). More than three or four wheels can be added to the system to generate sufficient flotation and traction. In some wheeled robots, steering is achieved by independently driven wheels. The wheels can be driven with differential speeds and forward/reverse motion, resulting in skidding and thus steering (as in a tank). Tracked vehicles use a similar steering mechanism and are used in outdoor rough terrain situations to achieve good floatation, traction, speed, and obstacle handling. While both wheels and tracks are faster and more efficient on reasonably flat terrain, the advantage of legs becomes evident when the surface is unprepared and rough. Legged robots are more maneuverable (turning radius = 0) and use less energy, resulting in less soil deformation. Legged robot design is inspired by biological systems. Main design challenges include the following issues:

- How to design a leg?
- How many legs to use?
- How to coordinate multiple legs?
- How to achieve static stability (when the robot stops) and dynamic stability (during motion).

Mobile robots are a very active and challenging research area. Their usage is mainly in special exploratory and one-of-a-kind tasks, and in unstructured environments. This brief review is intended to spark further interest in the topic. Reference to additional reading material is provided at the end of this chapter.

Today, most of the applications of mobile robots are beyond the scope of activities of the industrial engineer. His or her primary mandate is to improve the productivity, efficiency, quality, and safety of operations on the factory shop floor. Automation with industrial robots, when properly understood, justified, and correctly implemented, can be of great assistance in achieving these goals.

SUMMARY

The limitations of a given robot configuration, work space, and control system are the main factors to consider when selecting an industrial robot for a specific type of application. Industrial robots are not really general-purpose machines capable of being used for almost any task, as the inexperienced user may be misled to believe from their definition. In planning a robotic application, the scope of such application has to be carefully defined. Only then is it possible to proceed to a selection of a robot with configuration, work space, control system, and all the other technical specifications such as payload, power system, speed and accuracy, that are the best fit and most cost-effective for the application at hand.

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BIOGRAPHY

Jacob Rubinovitz, Ph.D., is a senior lecturer at the Faculty of Industrial Engineering and Management of the Technion. He headed the Robotics and Computer Integrated Manufacturing Lab between 1988 and 1995. Rubinovitz was a visiting assistant professor of industrial and management systems engineering at the Pennsylvania State University (1987–1988), and a

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CHAPTER 14.9

PRODUCTION FLOW STRATEGIES

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The four major factors contributing to production flow are the product, production environment, facility layout, and operational strategy. First, we detail elements related to the product including the type and size, degree of customization, type of demand and expected lead time, production volume, life cycle, and complexity. The effect of production environment and factory layouts is described next. We then discuss how various operational strategies such as scheduling approaches, order sequencing, and degree of automation impact the production flow. We conclude by highlighting production flow strategies that result in the least total cost of manufacturing. By effectively managing the production flow, a company can realize key strategic advantages.

INTRODUCTION

Production flow refers to the movement of the product through the facility. Although this concept is not difficult to understand, in practice we find that there are numerous techniques and levels at which the concept can be applied on the shop floor. Moreover, many companies use production flow strategies as a competitive advantage. Factors that affect the production flow can broadly be grouped into the following categories:

Product
Production environment
Facility layout
Operational strategy

Some of these factors can be controlled by the company, while others are dictated, for example, based on the specific product or customer demand.

Ideally, the product flow should be continuous with minimal disruptions throughout the production process. This strategy recognizes that a constrained or blocked production flow adds no value to the process. Where companies differ, however, is in how they achieve specific strategies and how the strategy employed contributes to one of the three universal shop floor metrics: *quality, cost,* and *time.* These metrics are applicable to any shop floor since a manufacturer in a competitive global economy must produce goods *better* (high level of quality), *cheaper* (at the least cost), and *faster* (shorter throughput times). This chapter will explore and detail factors affecting production flow and conclude with a description of the various production flow strategies that lead to the least total cost of manufacturing. Finally, a simple technique for analyzing production flow will be presented.

FACTORS AFFECTING PRODUCTION FLOW

Product

The type and size of the product will affect the production flow. The type of the product refers to whether the product is discrete or nondiscrete. Examples of discrete products include those that can be easily discerned or counted such as an engine, an automobile, a drive shaft, a coffee maker, or a washing machine. In contrast, nondiscrete products are measured or metered as opposed to being counted. Examples include paint, resin, steel, flat glass, oil, or flour. The size of these products, especially discrete products that are either extremely small or large, will require more specialized machines and fixtures to hold them [1]. Very large products such as a ship or building will generally require the movement of resources and operations to the production site, in contrast to moving the product to the production site as in the case of a motorcycle.

Product customization can greatly affect production flow. While consumers push for greater customization, manufacturers realize the expense associated with customization. A clear illustration of this selection of options occurs in the automobile industry. At the early inception of the mass marketing of the automobile to the general public, Henry Ford stated that the consumer could have it (the Model T) in any color they liked, as long as it was black. This approach (although extreme) allowed for the production of a relatively affordable and the first mass-produced automobile. Chevrolet, who had perhaps a keener sense of the customers' needs, launched a marketing effort to begin offering its automobiles in a variety of different colors, winning significant market share. In the 1970s and 1980s, U.S. automobile manufacturers took customization to the opposite extreme by offering their customers virtually unlimited choices in options. At one point, it was reported that the Chevrolet Citation was available in 32,000 versions, and the Ford Thunderbird was available in 69,000 versions. During the same period, the Honda Accord, manufactured by Japan, was sold in only 32 versions in the United States [2].

When automobiles are being manufactured in tens of thousands of versions, it is impossible for car dealers to stock all of the various configurations. This suggests that these models would need to be sold in a make-to-order environment. Although inventory is reduced in a make-to-order environment, a primary disadvantage is that customer delivery date is delayed and car dealers lose sales from customers who prefer to drive home with their new automobile at the time of purchase. In contrast, with the Japanese approach of fewer configurations, vehicles can be more easily stocked, and *impulse buyers* can immediately fulfill their need by driving home with their new purchase. With respect to the trade-off between customization and standardization, what is needed is a happy medium—manufacturers strive to limit customization where possible, while still satisfying customer requirements. Strategies being used in the automobile industry to support this middle-of-the-road solution are to provide as a standard feature those features that were once considered to be options. A good example of this is air conditioning. Today, in most automobiles sold in the United States, air conditioning is a standard feature. Another approach to the customization versus standardization dilemma is to package options together. For example, a car model may come in a deluxe, midline, and economy package. In this scenario, the deluxe model would come with all of the options, the economy model would have virtually no options, and the midline model would be somewhere in between. This approach will satisfy most customers while at the same time offer a cost-effective solution to the manufacturer.

Production flow varies depending on type of demand and expected lead time. Manufacturers often rely on make-to-stock strategies when customers demand standard, off-the-shelf products immediately and are not willing to wait to receive the product. Manufacturing strategies are also effective when there tends to be a high degree of product substitutability. An example of a make-to-stock product would be a toaster or television set. Make-to-stock assembly shops will generally need to make a significant investment in inventory to provide a variety of product configurations. Alternatively, an assemble-to-order strategy can be used when customers want products quickly, but not immediately. Here, customers select from a set of limited and specific options, thus establishing a trade-off between *time to deliver* and *level of customization.* Examples of products that are manufactured in an assemble-to-order environment include automobiles, and even submarine sandwiches. The third type of demand strategy is called either make-to-order or engineer-to-order. In this environment, the customer's requirements are very special or even one of a kind. Make-to-order products are high in design content and tend to be more expensive to make. Customers are willing to tolerate a long lead time. The commercial aerospace industry manufactures make-to-order aircraft with each airline carrier having unique requirements and configurations.

The volume of production will affect the production flow and especially the physical facility layout. Manufacturing in small batch sizes (< 10) tends to be produced in a job shop mode. In this environment, labor content of the product is relatively high with a lower degree of automation. In contrast, mass-produced items tend to have low levels of labor and high levels of automation. Layouts that use flow shop strategies will be more readily used to support continuous, dedicated repetitive, and batch flow strategies. Cellular manufacturing is a specific layout used to support flow type manufacturing.

The life cycle of a product (from concept to closeout production) typically has a significant effect on production flow. Typically, this cycle can be broken down into four major phases: conception, design, production, and divestment. The length of the entire life cycle, as well as the length of each phase within the life cycle, can vary dramatically depending on the product and the competition. For example, in the computer industry, we see a very short product life cycle for computers with new products being introduced to the market more rapidly. These newer models have faster processing, more memory, and more computing capability than their predecessors. And, the costs continue to fall. In other industries such as commercial aerospace, aircraft manufacturers typically make commitments to customers to supply spare parts for the reasonable life expectancy of the aircraft. Thus, along with a need to produce current products and parts, these manufacturers invest heavily in support/maintenance production. These scenarios described in the computer and aircraft industries suggest that production flow should be adaptable, that is, has the ability to produce different manufacturing requirements without disruption to the manufacturing operation.

The product complexity (number and degree of standardization of subparts) and subsequently the repetitive nature of production (time between successive units) also affects production flow. In general, greater complexities and time between production of successive units will lead to more inefficiencies in the production flow, higher investment in inventory, and higher costs. Manufacturers should limit to whatever extent possible the amount of complexity and strive towards a more repeatable production process. In the end, these factors will be dictated by the customer who ultimately has the final say on the product configuration.

Production Environment

As a society becomes more affluent, consumers demand a greater variety of products and options. John Naisbitt [3] describes today's Baskin-Robbins society where everything is available in multiple flavors. However, this places an additional burden on the manufacturer who must not only compete in a global environment based on price, quality, service, and speed to market, but must also incorporate flexibility into the shop floor. It is then no surprise that batch sizes have been declining. Half a century ago, mass production consumer durables was the norm; now most U.S. manufacturers produce in a batch mode, with more product types, but smaller batch sizes. Figure 14.9.1 describes the continuum between product variety and volume and shows how the type of production environment is a function of these factors.

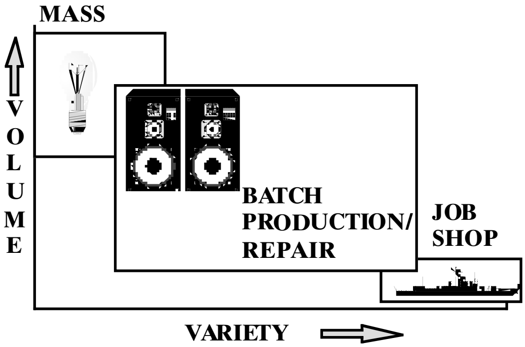

FIGURE 14.9.1 Production environment categories. *(Source: B. Bidanda and R. E. Billo, Presentation to Fleet Maintenance Facility—Cape Breton, February 1997.)*

There are three major types of production environment in discrete manufacturing: mass production (high volume, low variety), job shop production (low volume, high variety), and batch production (medium volume, medium variety). Nondiscrete manufacturing (process industries such as chemical and food processing) are a subset of mass production. Customers today demand the quality and low price characterized by mass production, but also the variety characterized by batch/job shop production. It is intuitively obvious that production flow is more easily streamlined in a mass production environment where all production follows a single path.

Facility Layout

The type of production environment is usually a determining factor in the type of layout employed, except in cases where the layout of machines and workstations in a manufacturing organization has evolved over the life cycle of the organization. Classical facility layout schemes for both the manufacturing and assembly environments include

Continuous flow layout
Product-type layout
Process-type layout
Fixed layout
Cellular-type layout

Continuous Flow Layout. A continuous flow layout scheme is generally utilized in the processing of fluids, chemicals (liquid or solid), or other bulk products. Here, a product is not a discrete entity, rather quantities of a product are typically metered into some sort of bulk storage container. Products in a continuous flow line can be divided into any size lot simply by adjusting the container size. Examples of continuous flow lines would include the refinement of crude oil into various petroleum products and the grinding of flour. Figure 14.9.2 illustrates a continuous layout configuration. All of the scrap copper flows through the factory in a similar sequence and thus production flow is characteristically simple and straightforward.

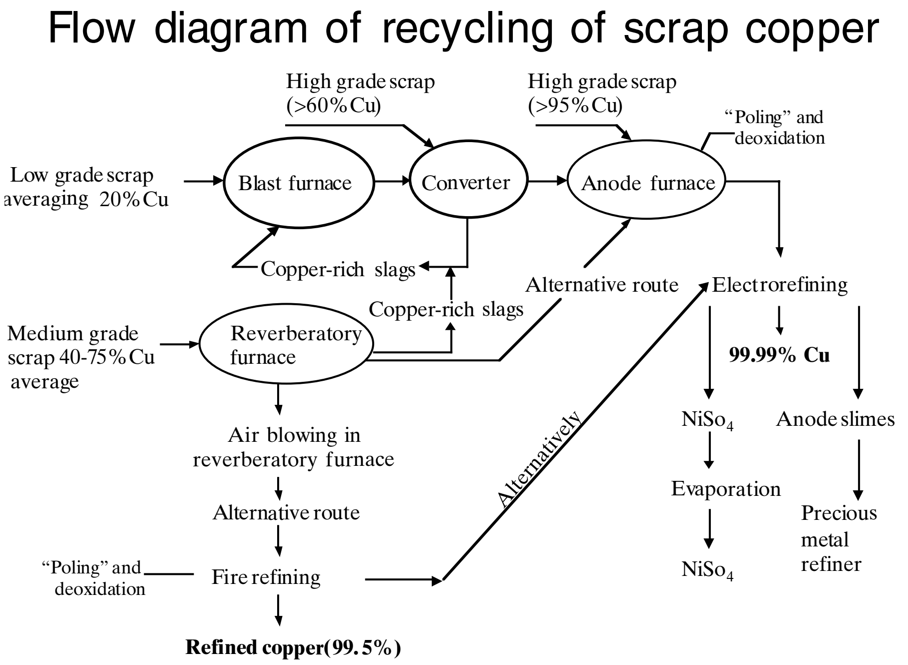
Flow diagram of recycling of scrap copper
High grade scrap (>60% Cu)
High grade scrap (>95% Cu)
"Poling" and deoxidation
Low grade scrap averaging 20% Cu
Blast furnace
Converter
Anode furnace
Copper-rich slags
Alternative route
Electrorefining
Copper-rich slags
Medium grade scrap 40-75% Cu average
Reverberatory furnace
99.99% Cu
NiSo4
Anode slimes
Air blowing in reverberatory furnace
Alternatively
Evaporation
Alternative route
Precious metal refiner
"Poling" and deoxidation
Fire refining
NiSo4
Refined copper(99.5%)

FIGURE 14.9.2 Example continuous flow layout. (*Source: J. J. Moore,* Chemical Metallurgy, *Butterworths, London, 1981, p. 290.*)

Product-Type Layout. A product type or dedicated repetitive flow layout is similar to the continuous flow line; however, in this case the product is discrete. Each set of machines (or line) is arranged so that only one product is manufactured on each line. It is also repetitive with large volumes of products manufactured in each line to justify the investment in dedicated equipment. Minor adjustments can be made to change color or perhaps apply a different marking onto the product with minimal setup time. An example of the use of a dedicated repetitive flow line would be an injection molding process used to manufacture plastic safety helmets. In this case, all helmets may be the same size (one-size-fits-all philosophy); however, the color and company logo applied to the helmets may vary. Figure 14.9.3 illustrates a product-type layout with four lines, each with a set of dedicated equipment. Production flow is again straightforward and streamlined and the production environment that this type of layout is most suitable for is mass production.

Process-Type Layout. A process-type layout is characterized by the grouping of similar equipment by function. Figure 14.9.4 depicts a typical process-type layout. Here, work centers

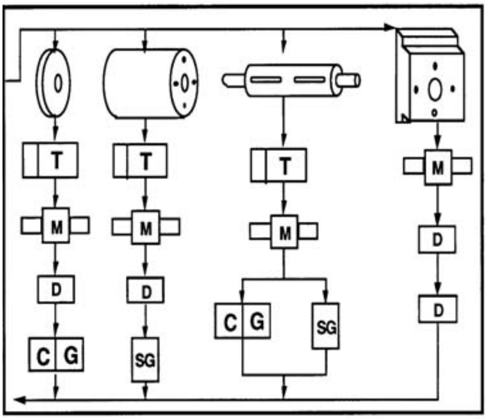

FIGURE 14.9.3 Example product-type layout. *(Source: B. Bidanda and R. E. Billo, Presentation to Fleet Maintenance Facility—Cape Breton, February 1997.)*

are organized by process into turning (T), milling (M), drilling (D), center grinding (CG), and surface grinding (SG). In this type of layout, jobs travel from one work center to the next in a unique prespecified sequence. This layout is specifically designed to support a wide diversity of product flow, although dominant patterns may appear. Flow patterns for four types of products can been seen in Fig. 14.9.4. Note that all jobs do not travel to the same number of work centers or to the same machines in the work centers. Also, there is nothing to prevent the flow from going back to a previous work center.

This type of layout is used mainly for job shop production, where orders are processed in very small batches (perhaps even as low as one). This is due to the unique requirements of each order, and typically, batch size is generally equal to the order size. This creates an environment with a large number of small orders with each order having perhaps its own unique

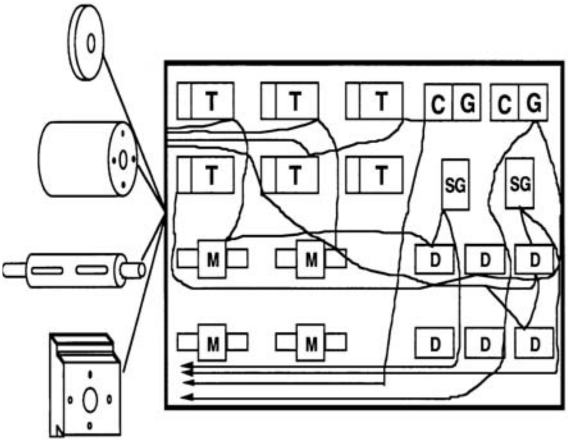

FIGURE 14.9.4 Example process-type layout. *(Source: B. Bidanda and R. E. Billo, Presentation to Fleet Maintenance Facility—Cape Breton, February 1997.)*

routing. This type of processing requires detailed planning and control as a result of the unique flow patterns and the separation of work centers. Thus, setups and work-in-process inventory levels tend to be high, work center utilization may vary greatly, and actual run times can be a small percentage of total lead time. Examples would be making prototypes of new products, or making user-specific machines, tools, or dies. If the flow pattern of parts produced in a typical job shop layout were superimposed, the resulting pattern would begin to resemble a bowl of spaghetti; thus, this type of production flow is often referred to as spaghetti-type manufacturing flow. Of all the classical layouts, this type of layout and associated flow pattern results in the most number of moves, the highest setup times, and the longest moves for each manufactured product.

Fixed Layout. Fixed site (or project) production is characterized by moving equipment, tools, material, and personnel to the production site. In this environment, highly skilled workers build the product per detailed customer specifications in order quantities often equal to one. Examples of this type of process include road construction, shipbuilding, erecting a building, or building a bridge. Obviously, the type of production environment that is characterized by a fixed layout is also a job shop production. Since product flow is not an issue here, the most appropriate method to increase efficiency of the production process is to focus on organizing worker teams and the creation of zoned areas within the product. This will help ensure that teams work in unique zoned areas at specified times and do not get in each other's way. A secondary objective is to minimize the number of teams (and people) needed for a given throughput time.

Cellular-Type Layout. As we move away from a product-type layout where a small number of products are manufactured on dedicated lines, batch sizes are reduced, and the number of batches for a given set of machines will increase. A product-type layout no longer becomes efficient because one cannot justify a dedicated line for each batch or product type. Also, the inefficiency that characterizes a job shop layout is also not cost-effective in today's competitive environment; here, a cellular-type layout is most effective.

In this type of layout, *families* of batches and parts that utilize similar machines, labor skills, or tooling are grouped together to form cells [4]. Moreover, each family of parts has its own unique cell where the production flow pattern is streamlined. The crucial step here in establishing an effective cellular layout is to form the best families or cells. This step utilizes the principles of group technology (GT), a concept first applied in the western world by John Burbridge and popularized in the United States by Inyong Ham [5]. Part families can be formed in a variety of methods ranging from a manual method (for shop floors with few parts) to more formalized techniques such as production flow analysis or clustering heuristics.

After cells of parts (or machines) are formed, they are typically organized into a linear or U-shaped configuration (as shown in Fig. 14.9.5). Parts *A, B,* and *C* flow through the first cell and parts *D, E,* and *F* flow through the second cell. Because work flowing through these cells is for a family of products, it can flow through relatively quickly because the cell design was based on production flow. Furthermore, changes to the production rate can easily be made because a machine operator can operate one or more machines depending on the required throughput time. An efficiently designed and operated cell will have standard operating procedures for different throughput times and production rates. In this type of layout, setups and material moves are minimized, and scheduling is relatively simple compared to a job shop. The primary challenge here is in balancing the capacity of each machine within the cell as well as synchronizing cell production. In essence, this type of layout strives to capture the efficiency of a product-type layout along with the flexibility of a process-type layout.

Operational Strategy

Operational strategy pertains to various factors including scheduling approaches, order sequencing, and degree of automation.

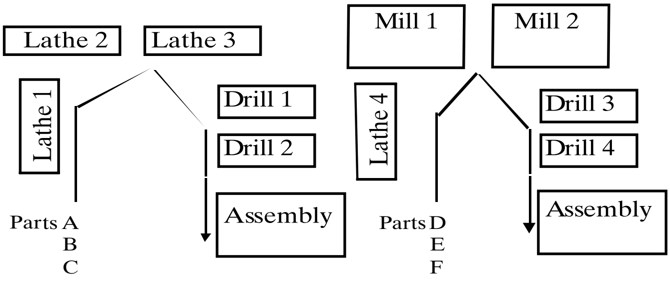

FIGURE 14.9.5 Cellular-type layout.

Scheduling Approaches. There are three commonly used scheduling approaches: *push, pull,* and *drum-buffer-rope.* The push approach is the oldest and forms the foundation for the traditional materials requirements planning (MRP) systems. In an effort to reduce inventory levels and subsequently costs, many manufacturing firms have moved from MRP systems and have embraced a philosophy more recently developed by the Japanese called just-in-time (JIT). Rather than using a push approach, the JIT philosophy is based on a pull approach. This pull approach has gained wide acceptance throughout industry. In still another effort to improve production flow, most recently, E. M. Goldratt has developed the theory of constraints (TOC). TOC is based on a scheduling approach called the drum-buffer-rope (DBR), which is constraint-based.

In a push system, items are produced at times and in quantities as indicated by a schedule planned in advance. In this manner, production (inventory) is pushed from upstream steps in the process to downstream steps in the process. The push system can build excessive and unneeded inventory when delays in the replanning of the schedule occur resulting from changes in production requirements.

Pull scheduling has evolved from the JIT philosophy. Taiichi Ohno, of Japan's Toyota Motor Corporation, is recognized as being the father of JIT. Although this philosophy is fairly new to the United States, it gained widespread support in Japan in the early 1970s. JIT as defined by Robert Hall [6] is to "produce products the customers want. Produce products only at the rate customers want them. Produce with perfect quality. Produce instantly—zero unnecessary lead time. Produce with no waste of labor, material, or equipment—every move with a purpose so there is zero idle inventory. Produce by methods which allow for the development of people." JIT includes all manufacturing activity ranging from the supplier to the customer, and from top management to the line worker. The major underlying elements of JIT include manufacturing excellence, continuous improvement, identification and elimination of waste, simplicity, flexibility, visibility, and people. Its main objective is to minimize inventory by eliminating non-value-added activities. The pull approach to scheduling means that the downstream steps in the process will signal production in the upstream steps in the process to fill demand, that is, build what is needed and when it is needed. A *kanban* (a Japanese word meaning card) is a commonly used signaling method.

The DBR is a scheduling technique developed by Goldratt and used in the TOC [7,8]. The DBR approach consists of four primary steps: (1) identify the constraint, (2) sequence jobs on the constraint, (3) decide on the size of the constraint buffers, and (4) decide on the size of the shipping buffers. In this approach, the process batch size does not need to be equal to the transfer batch size. The *drum* in this approach refers to the constraint. It is the constraint that beats the drum or sets the pace of the process. All other steps in the manufacturing process should be aligned with the constraint, because the constraint will determine the maximum system output. For example, if an upstream step in the manufacturing process produces at a rate faster than the constraint, excess inventory will queue in front of the constraint. In the DBR approach, the *rope* refers to the time offset between each process. It ties each process together to ensure that they do not get out of synch—so that one process does not get further ahead of another. And finally, the *buffer* refers to the material at the constraint. As in JIT, the TOC attempts to eliminate unnecessary inventory. However, in the TOC, inventory or a buffer is placed strategically in front of the constraint to ensure that statistical fluctuations and system dependencies do not starve the constraint or cause it to be without work. Capacity buffers are used at nonconstraint resources to break system dependencies.

Order Sequencing. When multiple orders are in queue at a work center, a decision must be made as to the sequencing of the orders, that is, which order should be processed first, second, and so forth. The five most commonly used order sequencing rules are first in, first out (FIFO), shortest processing time (SPT), earliest due date (EDD), minimum slack time (MST), and critical ratio (CR) [9]. As the name implies, orders are processed at each work center in the order in which they arrive using the FIFO sequencing rule. Using the SPT rule, orders are ranked in order of the total processing time remaining and processed from shortest time to longest time remaining. Although the literature reports that the SPT rule produces good results with respect to average performance measure levels (e.g., average order lateness), one disadvantage of this method is that orders with excessively long processing times are usually completed well after their actual due dates. Orders are ranked in due date sequence and processed beginning with the first due date in the EDD method. This approach is reported to achieve best results when all orders have similar processing times. In the MST method, orders are processed from smallest to largest slack time. In this application, slack time refers to the due date less the remaining processing time. In the critical ratio calculation, the CR is calculated by subtracting the current date from the due date and then dividing this quantity by the normal manufacturing lead time remaining. Orders are then prioritized from lowest to highest CR. These heuristics can be used in conjunction with each other. For example, a hybrid heuristic that is often used combines SPT and EDD to achieve efficient processing of jobs while adhering to the due date requirements.

Degree of Automation. Manufacturers can utilize automation as an operational strategy to improve and streamline material flow. Automation, when used effectively, will reduce setup times and labor costs associated with building the product and is most applicable when production is highly repetitive and volumes are high. However, automation is usually expensive and unless these costs are offset by resulting increased efficiencies, will result in increased product costs. For example, automation is often used at a bottleneck operation to decrease processing time and subsequently increase quality, capacity, and production rate.

PRINCIPLES OF EFFICIENT PRODUCTION FLOW

The best production flow strategies are those that result in the least total cost of manufacturing.

Product Should Always Move Forward

The most efficient product flows start at one end with accumulation of raw materials and subassemblies and progress sequentially to the other end with the final stocking or shipment of the product. The process tends to be forward moving with little or no backtracking. Backtracking can be a sign of inefficiencies in the process, such as quality problems, that result in rework. Moreover, confusion with respect to order sequencing and priorities may prevail at the work center as products have varying degrees of completion. A legitimate reason for backtracking would be the sharing of similar machinery during subsequent steps in the process as a result of excess capacity.

Keep the Product Flowing as Continuously as Possible

Continuous production flow is characterized by the frequent movement of small lots [10]. There are five distinct components of lead time: queue, setup, run, wait, and move. Queue refers to the time waiting before the operation begins. The time getting ready for the operation constitutes the setup time, and the actual time to perform the operation is the run time. The wait is the time waiting after the operation ends. And finally, the move refers to the time required to physically move the order between sequential operations. Of these five components, only the run adds value to the order. The other four components are considered to be non-value-added activities. Strategies that reduce the time spent performing non-value-added activities are necessary. For example, a philosophy that builds only what is needed when it is needed will tend to eliminate excessive work-in-process inventory in the facility. This will contribute greatly towards eliminating queue and wait times. In their effort to move towards JIT production, the Japanese have developed numerous strategies to reduce setups. First, the setup process is closely studied. External setup operations (those that must be performed while the production process is halted) are converted to internal setup operations (those that can be performed during the production process) where possible. In addition, tools, fixtures, and jigs that are needed to perform the setup are purchased and dedicated to the particular machine requiring the setup. With respect to move time, we find that it is virtually eliminated where cellular manufacturing is being utilized.

Non-value-added components of lead time can also be reduced through operation overlapping and operations splitting. Operation overlapping is a strategy in which the transfer batch size to the subsequent production or assembly operation is smaller than the order batch size. In this manner, operations overlap, thus reducing overall assembly time. Figure 14.9.6 shows an example of overall assembly time with and without operation overlapping.

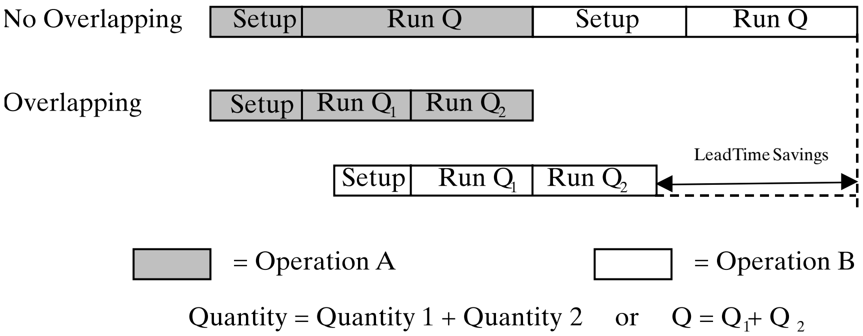

FIGURE 14.9.6 Operation overlapping.

Operation splitting is achieved when the order is split into two or more suborders and run in parallel on the same machine type. As with operation overlapping, overall assembly time is reduced. Figure 14.9.7 shows an example of this savings in assembly time and overall throughput time. Two cases are shown: *without* setup offset and *with* setup offset.

Minimize Disruptions While Order is Being Produced

Disruptions to an order while it is being built result in higher costs. Consider a common practice, an expediter halts the processing of an order at a work center to begin the processing of a *hot* order that is past due. This will typically require teardown and setup of the work center

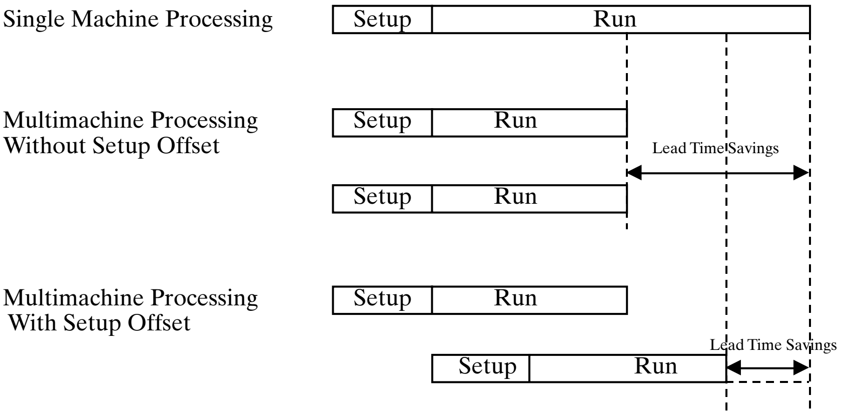
Single Machine Processing
Setup
Run
Multimachine Processing Without Setup Offset
Setup
Run
Lead Time Savings
Setup
Run
Multimachine Processing With Setup Offset
Setup
Run
Lead Time Savings
Setup
Run

FIGURE 14.9.7 Operation splitting.

to accommodate the hot order. When the work center is free to resume processing the original order, there may be a need to perform a new setup, and use overtime to get this order back on schedule. Thus, although the expediter may have achieved his or her goal to process the hot order, this success came at the expense of another order that now costs more to build.

Modern management philosophy would consider the expediting process to be a non-value-added activity, and in the ideal manufacturing world, there would be no need for expediting because the process would have flexibility and adaptability built into it.

Production Flow Pattern Should Be Adaptable

Per Tompkins [10], manufacturing adaptability refers to the ability to produce different manufacturing requirements. Thus, adaptability includes two components: flexibility and modularity. A manufacturing or assembly operation is flexible if it can change what is produced without disruption to the operation. And it is modular if the production volume can be expanded or contracted without altering the manufacturing approach. For example, consider a shop floor that assembles bicycles. If the assembly cells that assemble mountain bicycles and road bicycles for both women and men without any change in machine setup, the shop floor meets the criterion for flexibility.

Flexible manufacturing necessitates focused factories, small production lot sizes, versatile equipment, and multiskilled workers [10]. The term *focused factory* does not imply that the entire facility concentrates on making one major product or product line, but rather that there can be multiple focused factories within the facility that each focus on manufacturing a particular product or product line. If lot sizes are large and production runs are long, changes to what is produced will require a stop and eventual restart of the production order. This interruption does not support continuous flow. Small lot sizes will help to minimize this disruption. Equipment that is versatile with respect to feeds and speeds, and future hardware and software upgrades are most desirable. A small adjustable piece of equipment will most often be preferred to a large dedicated machine. Perhaps the largest opportunity to increase flexibility of assembly or manufacturing operation lies in the development of multiskilled workers. The Japanese have realized long ago that people—not machines—are their greatest investment in flexibility. The cost to retrain or reassign workers is small in comparison to the cost to retool or redeploy equipment. Impact on flexibility should be considered when examining new investments in resources. For example, a small incremental cost that provides a large amount of future flexibility would be an attractive investment.

Operations become more modular when facilities, departments, and time become more modular [10]. Facility expansion or contraction using the spine approach [11] maximizes modularity. In the spine approach, each of the focused factories of the facility are located along the exterior walls (perimeter) of the facility, while the spine is centrally located. The spine houses all critical functions necessary for the operations and control of the facility as a whole. Typically this would include the communications and material-handling functions. In this manner, each focused factory within the facility may be expanded or contracted independently of one another with minimal disruptions to core business processes. Time becomes more modular when the workforce is multiskilled. In this manner, workers can be reassigned from idle to busy operations. In addition, system throughput can be increased without changes in operating hours or in worker assignment simply by staggering the break and lunch periods of the workers.

Production Flow Should Enhance Quality

There must be a move from product inspection toward process acceptance. This enhances production flow because the number of moves is reduced since process acceptance is typically done on the machine or on the shop floor as opposed to a separate inspection station. Some manufacturers believe that quality can be inspected into the product. Today the inspection process is considered to be an unwanted step in a manufacturing environment, and we know that even 100 percent inspection will not ensure 100 percent quality. What works better is to strive for process acceptance, where the process is designed, monitored, and audited so that it will only allow high-quality parts to be manufactured. Workers are given responsibility, as well as authority, for ensuring the quality of their parts/products. The quality assurance department is no longer responsible for quality, but rather takes a more active role in training and supporting the workers. In this manner, the process is designed to manufacture only high-quality parts, thus eliminating the need to perform product inspection. Another technique that is used to improve quality is called *poka-yoke* [12]. This is a philosophy adopted from the Japanese. Literally, the term means foolproof or mistake-proof. For example, a control may limit how far a machine can cut into a part to prevent the cut from being made too deep.

Production Flow Patterns Must Account for Uncertainty and Dependencies

Goldratt [7] contends that all production systems contain statistical fluctuations and dependencies. Buffers can be used in a production process to decouple processing steps (eliminate the dependencies) and smooth out the production flow (reduce the fluctuations). Buffers can be in one of two forms: material and time. Material buffers, in the form of finished goods, are commonly used at the end of the manufacturing process to account for uncertainty in customer demand. Time (in the form of lead time) can be used in front of a bottleneck resource. For example, orders can proceed ahead of schedule to the bottleneck resource to ensure that this resource is always fully loaded.

ANALYZING PRODUCTION FLOW

Before one can make improvements in the production flow, we must first document the *as-is.* This can be done by employing one of the many process flow tools available to industrial engineers. These include process flow diagrams, process flowcharts, gang process charts, and the like. Some newer process flow techniques, such as the triple diagonal, are especially useful since they track information as well as product flow [13]. The level of detail in developing production flow diagrams must also be chosen before the study is conducted. For example, if one analyzes material flow through an entire shop floor, a left-hand/right-hand chart is obviously too detailed.

After the process flow through the facility has been documented and refined, one of the three universal shop floor metrics (usually time/distance) is incorporated into the result so that it may be evaluated. While this data is sometimes (though rarely) available, it is perhaps best to collect new data. Available data is often outdated, inaccurate, and does not categorize the performance metric into process steps.

A simple but effective method of categorizing this time data is through the use of travelers. A sample traveler form is shown in Fig. 14.9.8. The traveler would follow a set of parts from order entry to final part shipment. Date and time of entry and departure of a set of parts into each operation is noted. After a sufficiently large sample has been collected, the available data can be analyzed and bottleneck operations that constrain efficient production flow can be identified. Based on these results, special improvement projects or automation strategies can be employed to alleviate these bottlenecks.

Product:____

Task #	Description	In Date	In Time	Out Date	Out Time	Comments
1	assemble frame in fixture & weld					
2	paint frame					
3	bore crankcase					
4	install front deraillers					
5	install sprocket and crank					
6	assemble front fork					
7	assemble rear wheel & chain					
8	install front wheel, handlebar, and adjust					

FIGURE 14.9.8 Sample traveler.

SUMMARY AND CONCLUSIONS

We have shown how the product, production environment, facility layout, and operational strategy effect the production flow of the manufacturing process. There is a growing awareness throughout the manufacturing community regarding the importance of production flow strategies. By effectively managing production flow, a company can increase throughput and quality, and reduce material handling, inventory, and manufacturing lead time, resulting in key strategic advantages.

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BIOGRAPHIES

Kim LaScola Needy is an associate professor of industrial engineering at the University of Pittsburgh and a Wellington C. Carl faculty fellow. She received her B.S. and M.S. degrees in industrial engineering from the University of Pittsburgh, and her Ph.D. in industrial engineering from Wichita State University. She has obtained nine years of industrial experience at PPG Industries and The Boeing Company. Her research interests include activity-based costing, engineering economic analysis, engineering management, and integrated resource management. She is a senior member of IIE and a member of ASEE, ASEM, APICS, IEEE, SME, and SWE. She is a licensed P.E. in Kansas.

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SECTION 15

GOVERNMENT AND SERVICE INDUSTRY APPLICATIONS

Source: MAYNARD'S INDUSTRIAL ENGINEERING HANDBOOK

CHAPTER 15.1

INDUSTRIAL ENGINEERING IN GOVERNMENT

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his chapter will discuss industrial engineering (IE) in government. It concentrates on the U.S. federal government. However, in line with the international theme of the *Handbook,* we include a case study about the federal courts in Austria to show that IE is applicable beyond the U.S. federal government. In this chapter, we:

- Give a definition of the types of government organizations and some of their characteristics.
- Provide some history of IE in the U.S. federal government. The history shows a continuous stream of stimuli for IE services coming from the Executive Office or from Congress.
- Present several case studies to illustrate the application of IE approaches in government. One discusses the development of staffing requirements for the Austrian federal courts. Another discusses the application of IE at the Kennedy Space Center, a part of the National Aeronautics and Space Administration (NASA). A postal case study is also given.
- Discuss ways in which a new industrial engineer can work for or with the U.S. government, including sources of job opportunities.
- Conclude with a summary and discussion of future trends.

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GOVERNMENTAL ORGANIZATIONAL TYPES

Levels of Government

Government organizations (the formal infrastructure that operates the controls on the named sector) may exist at the following levels (the terms may vary from country to country and the list is not exhaustive):

1. Ward or borough
2. City or town
3. County
4. State
5. Country
6. Treaty group
7. International

There is great opportunity for industrial engineers in government service. The larger the governmental entity, the bigger the problems and the greater the opportunities for industrial engineers. There are two basic kinds of government organizations: those with physically stated objectives, and those with service objectives.

Organizations Having Physical Objectives

These organizations have objectives that can be stated in physical terms. They include:

- Road, bridge, airport, and other infrastructure construction and maintenance activity, including highway grass cutting, cleaning, repairing, and park maintenance; printing, binding, and engraving
- Cataloging and filing books and periodicals
- Production and maintenance of military supplies and hardware
- Warehousing and distribution, particularly of military supplies
- Waste removal and disposal

Organizations Having Service Objectives

These organizations have objectives that are stated in social or service terms. They include:

- Educational services
- Social services
- Police and military services, justice
- Loans and grants
- Procurement
- Regulation development and enforcement
- Operational control systems, such as those provided by the Federal Aviation Administration (air traffic control), the Internal Revenue Service (IRS) (tax processing and collection), and the U.S. Patent and Trademark Office (patent application processing)

INDUSTRIAL ENGINEERING IN GOVERNMENT

IE Techniques Applicable to Different Organizations

Table 15.1.1 shows NASA's perception of the scope of IE.

Organizations with Physically Stated Objectives. These organizations have many of the same characteristics as the private sector. Although the concept of profit does not occur, performance to budget does and so, too, do the criteria for success concerning productivity, efficiency, effectiveness, cost, quality, safety, timeliness, and social and political acceptability.

Organizations with Service Objectives. Those whose objectives may be stated only in service or social terms require additional techniques, resembling those used with white-collar workers, to identify outputs or results prior to the use of traditional techniques.

Impact of Labor Unions. Both types of organizations may have unionized workforces. Air traffic controllers, postal workers, and employees of the U.S. mint are represented by labor unions in the United States. In an example detailed in this chapter, the employees of the federal courts of Austria are unionized. The primary impact is that the unions must be persuaded to be supportive of the use of IE techniques and methods. This requires abiding by the labor contract and taking a participative approach that makes the union a partner in the IE program.

Opportunities for Wage Incentives. Wage incentives and pay-for-performance systems are generally nonexistent in the government. This is also true for quasi-governmental businesses such as public utilities. The public at large is sensitive to government waste, and there is a perception that incentive payments to governmental employees are like paying them extra money to perform the job for which they were hired. Nevertheless, some incentive pay schemes are in use at the IRS (for computer entry of tax returns) and for some work at the National Archives and Records Administration.

Effect of the Level of Government on IE Techniques. The level of government does not have any special effect on the use of IE techniques, although it does usually affect the breadth, scope, and complexity of the problem situations to which the techniques are applied.

SHORT HISTORY OF IE IN GOVERNMENT

From 1910 to 1917—Growth of IE in Government Manufacturing

Industrial engineering developed in the manufacturing branch of the U.S. government (printing and engraving, munitions and arms manufacturing) during the period from 1910 to 1917.

TABLE 15.1.1 NASA's Perception of the Scope of IE

Core industrial engineering capabilities	Examples
Process analysis and modeling	Process simulation, process control, root cause analysis, process reengineering
Management support systems	Metrics, performance measurement systems, decision modeling, risk analysis, cost-benefit analysis
Human factors engineering	Ergonomics, team dynamics, human error investigation/root cause analysis
Work measurement/methods engineering	Work methods analysis, task standards, associated measurement systems
Planning and scheduling systems	Scheduling techniques, schedule risk assessment, resource loading/leveling
Quality management	Facilitation, coaching, and support of cross-functional continuous improvement and benchmarking teams

Source: *IE Solutions,* February 1998, pp. 27–32.

This development paralleled the private sector. Little thought was given to applying it to the larger service sector.

Prohibition Against Time Study. In 1917, at the urging of organized labor, which felt that time study had been used abusively, Congress added a rider to the appropriations act that stated, essentially:

> None of these monies, nor no part of these monies, shall be used to pay the salary of, or any part of the salary of, any person who makes or causes to be made a study of any part of the time expended by a government employee between the time of punching in and the time of punching out.

Later, Congress made the use of time clocks, for punching in and punching out, illegal. To get a feel for the strength of this attitude, it is worth noting that the U.S. Department of Treasury in Washington, D.C., installed such clocks while Congress was considering the legislation. Displeased, Congress passed additional legislation forbidding the use of any appropriated monies for repairing time clocks. It is worth noting that the attorney general later ruled that the prohibition was valid only within the bounds of the District of Columbia, as constituted at the time of the legislation. As a result, time clocks were commonly used at other governmental installations.

Repeal of the Antitime Study Rider. In 1948, following World War II, Senators Flanders of Vermont and Taft of Illinois argued that the rider was nongermane to the appropriations bill. It further offered for prosecution for contempt of Congress various industrial engineers who, during the War, had applied IE techniques including time study to the analysis of various battle operations. The results had been profound. For instance, the time to place a battery of field artillery was cut in half. A change in the method of handling antiaircraft ammunition on Navy cruisers had the effect of doubling the firepower of the ships. Studies of the methods of target acquisition during kamikaze attacks greatly raised the kill rate. No one in Congress wanted to prosecute these individuals who had successfully applied IE techniques, and the rider was removed from the appropriations act.

1949 Presidential Directive on the Employment of IE

In 1949, President Truman issued Executive Order 10072, which stated:

> Agency heads are to take steps to assure themselves and the President that operations are being carried out with maximum efficiency and maximum economy.

Through a variety of approaches, agency heads blunted the intent of this directive. Problems were attacked, but were not clearly defined. Measurement was conducted with unclear units of measure. And service level was often excluded from study. The form of implementation became overly specific, substituting for intent.

In 1951, the Army founded the Ordnance Management Engineering Training Agency at the Rock Island, Illinois, Arsenal. In 1988, its name was changed to the Army Management Engineering College. The college has processed 17,000 students per year, greatly expanding the understanding of management engineering in the Army.

As the federal government grew, the need for efficiency persisted, and the concepts needed to solve problems needed to be broader in scope. In 1966, the Office of Management and Budget (OMB) issued OMB Circular—A-76. This is a government initiative to reduce costs by forcing government entities to compete against the private sector. The A-76 philosophy is to find the least costly method of accomplishing the work needed by government. This program is active at the time this chapter is being written. The Department of Defense (DoD) expects

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to study 170,000 positions under this program during the years between 1997 and 2002. An excellent discussion of OMB Circular—A-76 appears in the Winter 1998 issue of the *Society of Work Science* (*SWS*) *News.*

During the late 1970s and the 1980s, the military published a military standard—MIL-STD 1567A. The standard called for type-1 engineered labor standards (high accuracy: ±10 percent) on all defense work over a specified dollar limit. The DoD mounted a major effort to get contractors to comply with MIL-STD 1567A. While defense contractors did, and continue, to use standards in managing their businesses, by 1990 there was no longer special emphasis on compliance.

In April 1988, Executive Order 12367, "Productivity Improvement for the Federal Government," was issued. In response to this directive, the General Services Administration (GSA) is awarding "management, organizational, and business improvement services" (MOBIS) contracts to make it convenient for government officials wishing to improve the performance of their organizations to receive assistance from commercial organizations.

1993 Government Performance and Results Act

In 1993, Congress passed Public Law 103-62, the Government Performance and Results Act (GPRA). Its goals are to:

- Improve the confidence of the American people in the capability of the federal government, by systematically holding federal agencies accountable for achieving program results.
- Initiate program performance reform with a series of pilot projects in setting program goals, measuring program performance against those goals, and reporting publicly on their progress.
- Improve federal program effectiveness and public accountability by promoting a new focus on results, service quality, and customer satisfaction.
- Help federal managers improve service delivery by requiring that they plan for meeting program objectives and by providing them with information about program results and service quality.
- Improve congressional decision making by providing more objective information on achieving statutory objectives and on the relative effectiveness and efficiency of federal programs and spending.
- Improve the internal management of the federal government.

Congress wisely provided agencies with significant time to comply with GPRA. Strategic plans were to be prepared by September 1997. By March 31, 2000, program performance reports are to be prepared and submitted to the President and Congress. Further, GPRA offered managerial flexibility as an inducement to complying with accountability requirements. It said that, beginning with fiscal year 1999, performance plans may request waiver of existing controls, staffing levels, compensation levels, and prohibitions on transfer of funding between programs.

As of December 1998, GPRA was alive and well and continues to have Congressional support. GPRA is a significant driving force for the employment of IE and other management technology in the U.S. federal government.

CASE STUDIES

Austrian Federal Courts

Citizens criticize public inefficiency. Governing bodies cut spending and make high demands on administrators regarding effectiveness, efficiency, and employee morale.

A system called Personalanforderungsrechnung (PAR) was developed to deal with the various governmental pressures. *PAR* translates from the original German into *computation system for personnel demand.* PAR provides an objective measure of staffing requirements and was originally developed for and applied successfully in commercial banking situations. PAR was described in detail in Sec. 5, Chap. 7, of the fourth edition of *Maynard's Industrial Engineering Handbook,* (McGraw-Hill, New York, 1992).

This case example describes an application of PAR developed in cooperation with the Federal Chancellery of Austria and the Austrian Federal Ministry of Justice. This is an example of sound IE principles being applied successfully to an extremely complex work situation. It is an innovative adaptation of a commercial technique to a governmental situation.

The Austrian Federal Ministry of Justice (AFMJ) selected 32 of 193 district courts and 12 of 21 provincial courts for the pilot project. Workload in each provincial court had been evaluated according to the number of cases handled, regardless of complexity. The old allocation methodology caused an increase in backlogs at the larger courts handling more complex cases. Service to the Austrian citizens was diminished.

The participative implementation of PAR secured the buy-in of a wide range of interested parties. The judges were unionized, and agreement from their union was critical. The two levels of courts, provincial (higher) and district (lower) had 700 and 1100 judges, respectively. Each court had two categories of personnel trying cases—judges and registrars. Registrars were nonacademic judges who tried simpler cases.

PAR was developed under an Austrian-wide steering committee numbering 40 persons. They met 14 times during PAR development, and got decisions necessary to move PAR development to completion. Participation was extensive during the one-year PAR development project. There was a core team of 70 persons, and up to 400 judges participated in some manner. The total time taken by PAR development was nearly 1800 person-days (out of a total of 400,000 days worked during the year by judges and registrars).

The soundness of the technical approach enabled the presidents of county courts to allocate the total, mandated numbers of judges according to the actual case load as well as objective resource distribution at each location. Results from using PAR were widely accepted and useful in the budget discussions, including at the union level.

Following is a description of the technical approach used in measuring the Austrian judicial system.

Work Breakdown. Work is broken down between:

- *Infrastructure activities that are independent of quantity.* These include management, planning, budgeting, personnel administration, and special projects.
- *Operative activities that are quantity-dependent.* These include the various types of cases handled by the judges.

A careful top-down analysis of the work structure is an essential starting point for implementation of PAR.

Measurement Approaches. Various techniques are used to measure the time required for the many and varied types of activities. Measurement techniques used include:

- Interviews
- Structured self-reporting of activities and times
- Comparisons with known task times
- Estimates
- Predetermined motion-time systems

Some tasks measured in the PAR program took several years to complete. Others involved intense intellectual effort. These difficult-to-measure tasks were measured using an *equivalent* *value method* that was developed during this program. The equivalent value method is a combined time measurement procedure that determines the facts (files, applications, and incidents) to be estimated. Information on time is obtained through comparison with related facts and circumstances for which time requirements are known.

Complex situations were categorized by the type of case, and then by *difficult, average,* and *simple.* Each of these major groupings was further divided into three subcategories to refine the estimating approach. Special attention was given to the parameters in a case that caused it to jump between the three broad difficulty ranges.

Raw data were collected from existing court records and from self-reporting by the judges. In virtually all cases, no attempt was made to discard high and low times. Rather, a statistical analysis was made of the data, and definition of the groupings was made more precise. Reporting of equivalent values was made on a worksheet similar to that shown in Fig. 15.1.1.

Infrastructure activities (time required regardless of case load) are defined and a measurement is placed upon them. Infrastructure tasks include management, education, reporting, development of statistics, briefings, general consultation, projects, and special allowances for specific locations where activities must be performed in a distant location in the home building or in a satellite building. Management of the courts had the responsibility to assess whether the time values for these activities were realistic for the situation. An illustration of infrastructure activities and times is shown in Fig. 15.1.2.

At present, PAR provides for self-reporting of activities by the various judges and registrars. This raw data is compiled into reports for various levels or groupings. The system is in the process of being used as a nationwide controlling tool.

PAR reports are used annually at budget time to help prepare the budget for the coming year. PAR reports compare work credit earned with actual hours worked. Total hours include normal working hours, overtime hours, and substitution (or compensatory) hours.

The conceptual approach to PAR is shown in an overview in Fig. 15.1.3. It shows the two types of activities, the time spent, and the reported overall personnel utilization. It shows how the program can provide accounting information for budgeting, as well as head count information for personnel planning and backup for determining charges. The practical application, based on 1997 figures, led to a generally accepted increase of planned jobs by 53. A typical calculation sheet to determine personnel requirements in district courts is shown in Fig. 15.1.4.

The Kennedy Space Center

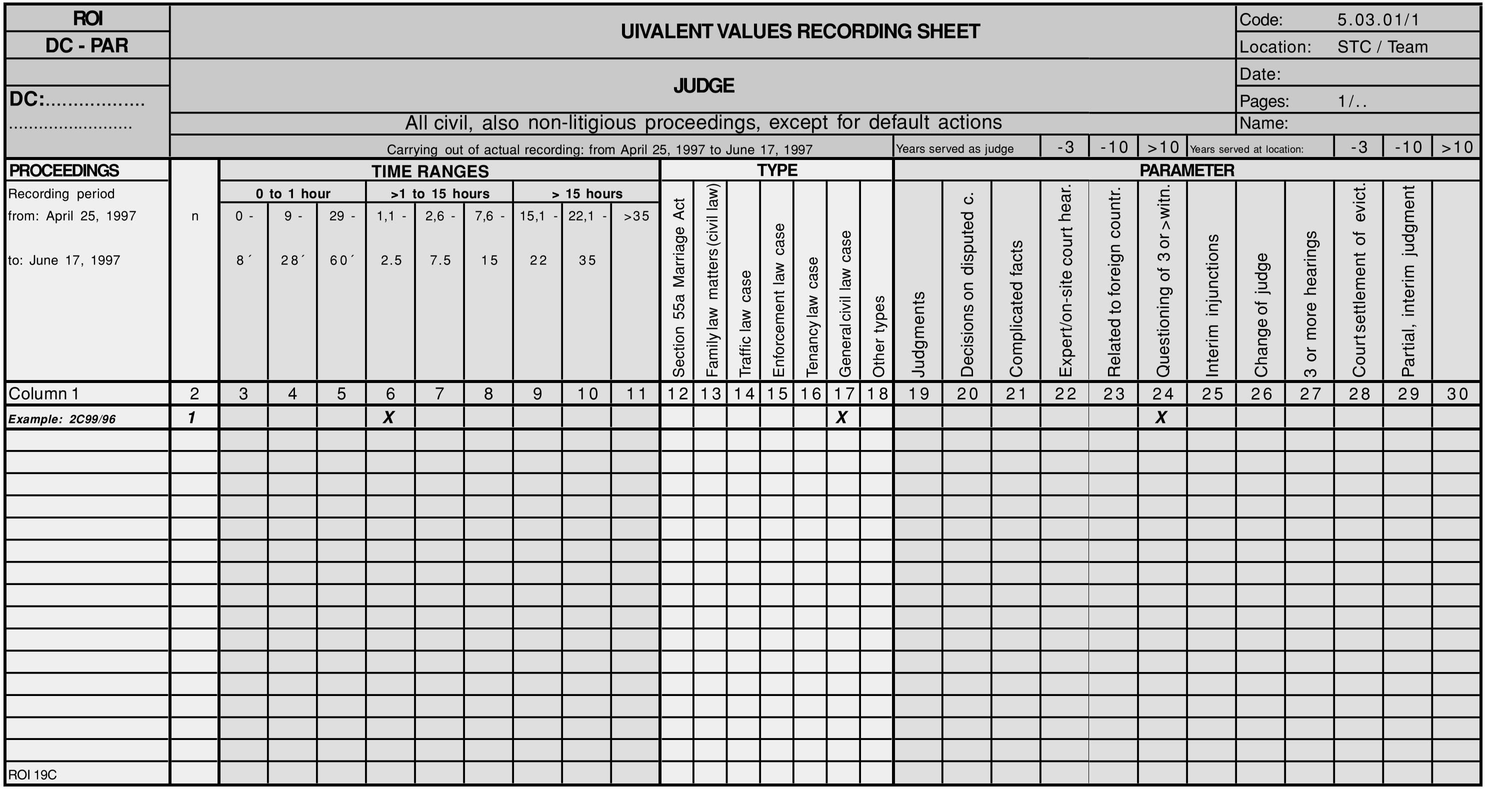
The Kennedy Space Center (KSC) operates a Small Business Innovation Research (SBIR) program to develop innovative concepts that meet NASA mission requirements. Small businesses bid competitively for SBIR contracts. Each successful SBIR project will go through three phases.

1. Feasibility and technical merit of the proposed innovation is established.
2. Further development of the most promising phase 1 innovations is funded based on scientific/technical merit, results, expected value to NASA, contractor capability, and commercial potential.
3. Complete the development of the innovation and make it commercially available.

Measurement of Orbiter Ground-Processing Activities. Work was measured for orbiter ground-processing activities at the Hypergolic Maintenance Facility at the KSC in Florida. NASA sponsored a test using a *best professional estimate* (BPE) for three operational maintenance instructions used by the maintenance facility.

The interest in measurement was to provide quick, inexpensive, yet consistent, estimates of work time, labor categories, and outside support for improved

- Planning and scheduling of resources
- Balancing the workforce with the amount of work to be completed



ROI DC - PAR	UIVALENT VALUES RECORDING SHEET	Code: 5.03.01/1 Location: STC / Team
DC:..................	JUDGE All civil, also non-litigious proceedings, except for default actions	Date: Pages: 1/.. Name:
	Carrying out of actual recording: from April 25, 1997 to June 17, 1997	Years served as judge -3 -10 >10 Years served at location: -3 -10 >10

PROCEEDINGS		TIME RANGES									TYPE							PARAMETER											
Recording period		0 to 1 hour			>1 to 15 hours			> 15 hours																					
from: April 25, 1997	n	0 -	9 -	29 -	1,1 -	2,6 -	7,6 -	15,1 -	22,1 -	>35	Section 55a Marriage Act	Family law matters (civil law)	Traffic law case	Enforcement law case	Tenancy law case	General civil law case	Other types	Judgments	Decisions on disputed c.	Complicated facts	Expert/on-site court hear.	Related to foreign countr.	Questioning of 3 or >witn.	Interim injunctions	Change of judge	3 or more hearings	Courtsettlement of evict.	Partial, interim judgment	
to: June 17, 1997		8´	28´	60´	2.5	7.5	15	22	35																				
Column 1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30
Example: 2C99/96	*1*				*X*											*X*							*X*						
ROI 19C																													

FIGURE 15.1.1 Computation of equivalent values recording sheet.

ROI	PROVINCIAL COURT - INFRASTRUCTURAL ACTIVITIES	Code: 8.03.02
PAR	WORK GROUP 5	Location: Date:
BG - LG		RM/Zin S 1/1
Classificat.	Infrastructural activities	Calculation mode
1	Judicial administration	Section 31 para 2 Court Organization Statute note 9/MSA
2	Education - active, passive, education of judicial trainees, trainee judges	4,5 % * the number of judges 3,6 % * registrars
3	Other reports, statistics, briefings, meetings, opinions and statements on bills and draft regulations, expert supervision by the judge	1,5 % * the number of judges 1,2 % * registrars
4	Court office hours for consultation in labor law matters, social law matters and Business Register matters	value per Provincial Court
5	Tasks related to individual staff members	
5.1	Professional representation	
	Federal chairman	60 % of working capacity
	Deputy of federal chairman	20 % of working capacity
	Provincial chairman reagon A	20 % of working capacity
	Provincial chairman reagon B	23 % of working capacitiy
	Members of the professional body on national level reagon A	12 % of working capacity
	Members of the professional body on national level reagon B	15 % of working capacitiy
	Members of the professional body on provincial level	7 % of working capacity
	If a professional representative holds several functions the planned time values are not to be summed up only the respective highest value is to be filled in	
5.2.	Representation of staff	
	Chairman of a committee responsible for more than 300 staff members	66 % of working capacity
	Chairman of a committee responsible for 151 to 300 staff members	50 % of working capacity
	Chairman of a committee responsible for 51 to 150 staff members	38 % of working capacity
	Chairman of a committee responsible for 20 to 50 staff members	25 % of working capacity
	Deputy	10 % of working capacity
	Chairman	5 % of working capacity
	Members of the committee convening ist meetings on principle at the location of the committee member	7 % of working capacity
	If a staff representative holds several functions the planned time values are not to be summed up only the respective highest value is to be filled in	
5.3.	Personnel division, external division	
	Members of the personnel division, appointed at the seat of the court	5 % of working capacity
	Members of the personnel senat appointed off the seat of the court incl. Travelling time (return ticket)	7 % of working capacity
	The regulations set for members of the personnel division also apply to members of the external division	
5.4	Staff members in charge of safeguarding equal treatment	according to official notice of exemption
5.5.	Projects Project instruction / time required according to the project instruction	
6	Location allowances according to objective requirements (e.g. Provincial Court 8700: 10 % of 1 full-time staff)	

FIGURE 15.1.2 Provincial court—infrastructure activities and times.

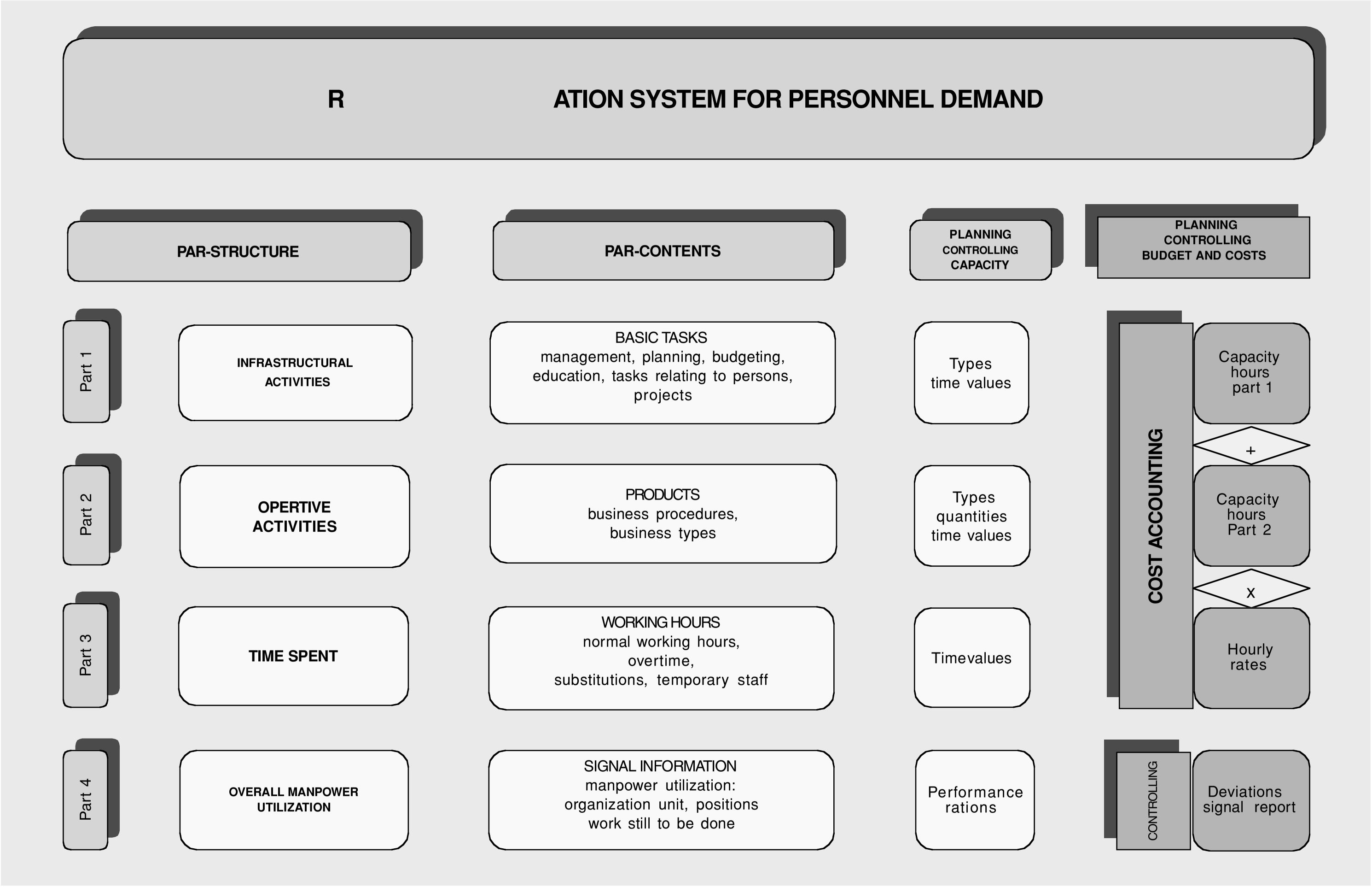
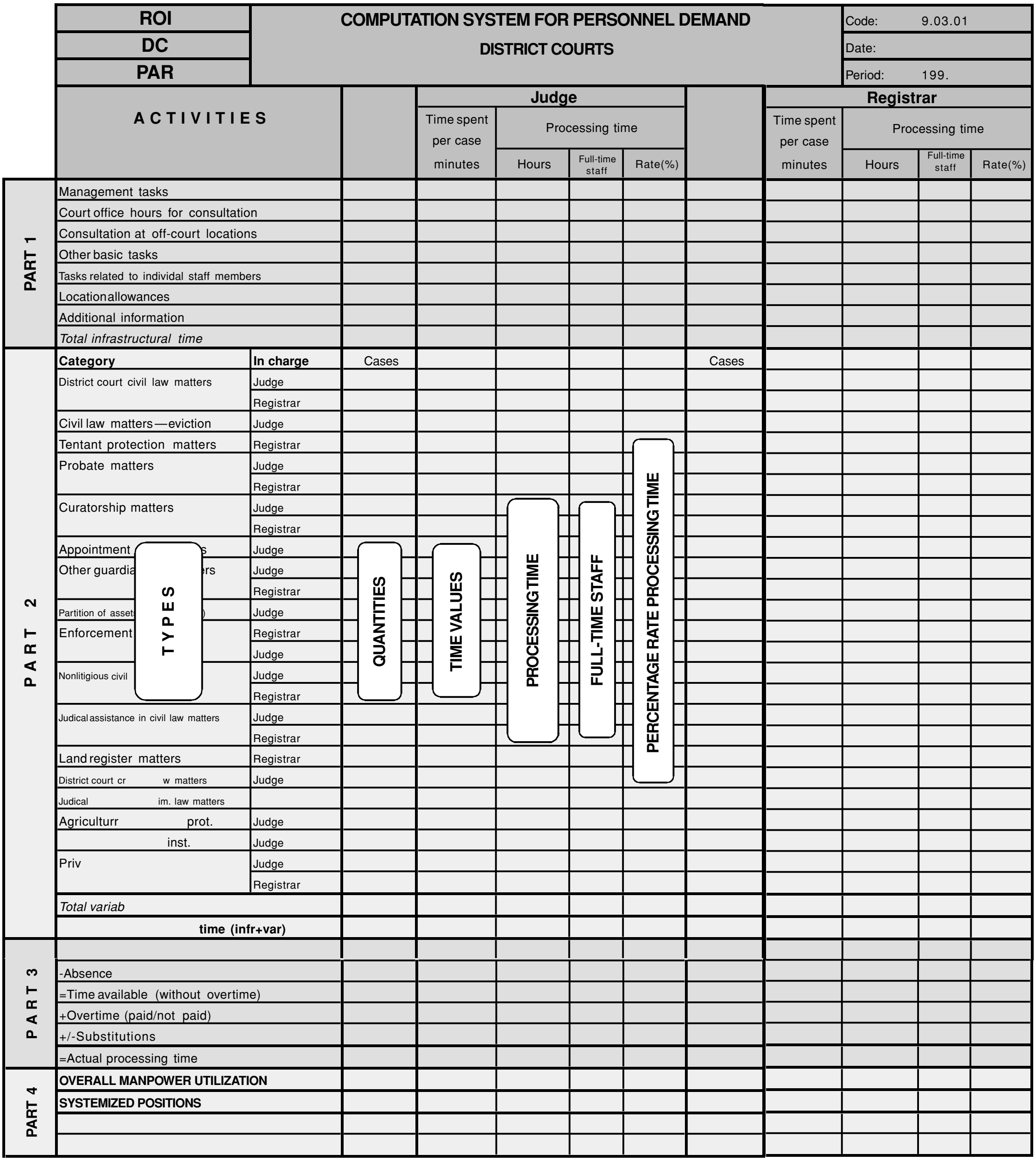

R ATION SYSTEM FOR PERSONNEL DEMAND
PAR-STRUCTURE
PAR-CONTENTS
PLANNING CONTROLLING CAPACITY
PLANNING CONTROLLING BUDGET AND COSTS
Part 1
INFRASTRUCTURAL ACTIVITIES
BASIC TASKS management, planning, budgeting, education, tasks relating to persons, projects
Types time values
Capacity hours part 1
+
Part 2
OPERTIVE ACTIVITIES
PRODUCTS business procedures, business types
Types quantities time values
Capacity hours Part 2
x
COST ACCOUNTING
Part 3
TIME SPENT
WORKING HOURS normal working hours, overtime, substitutions, temporary staff
Timevalues
Hourly rates
Part 4
OVERALL MANPOWER UTILIZATION
SIGNAL INFORMATION manpower utilization: organization unit, positions work still to be done
Performance rations
CONTROLLING
Deviations signal report

FIGURE 15.1.3 PAR computation system for personnel demand.



	ROI **DC** **PAR**		**COMPUTATION SYSTEM FOR PERSONNEL DEMAND** **DISTRICT COURTS**						Code: 9.03.01 Date: Period: 199.			
	A C T I V I T I E S			**Judge**					**Registrar**			
				Time spent per case minutes	Processing time				Time spent per case minutes	Processing time		
					Hours	Full-time staff	Rate(%)			Hours	Full-time staff	Rate(%)
PART 1	Management tasks											
	Court office hours for consultation											
	Consultation at off-court locations											
	Other basic tasks											
	Tasks related to individal staff members											
	Locationallowances											
	Additional information											
	Total infrastructural time											
P A R T 2	**Category**	**In charge**	Cases					Cases				
	District court civil law matters	Judge										
		Registrar										
	Civil law matters—eviction	Judge										
	Tentant protection matters	Registrar										
	Probate matters	Judge										
		Registrar										
	Curatorship matters	Judge										
		Registrar										
	Appointment s	Judge										
	Other guardia rs	Judge										
		Registrar										
	Partition of asset)	Judge										
	Enforcement	Registrar										
		Judge										
	Nonlitigious civil	Judge										
		Registrar										
	Judicalassistance in civil law matters	Judge										
		Registrar										
	Landregister matters	Registrar										
	District court cr w matters	Judge										
	Judical im. law matters											
	Agriculturr prot.	Judge										
	inst.	Judge										
	Priv	Judge										
		Registrar										
	Total variab											
	time (infr+var)											
P A R T 3												
	-Absence											
	=Time available (without overtime)											
	+Overtime (paid/not paid)											
	+/-Substitutions											
	=Actual processing time											
PART 4	**OVERALL MANPOWER UTILIZATION**											
	SYSTEMIZED POSITIONS											

FIGURE 15.1.4 Computation system for personnel demand—district courts.

- Measuring performance
- Controlling costs
- Providing a baseline for process improvement efforts

The experience with BPE recounted here is appropriate where there are written procedures for a maintenance action, as are available in aircraft maintenance, space shuttle maintenance, nuclear power station maintenance, and other maintenance actions or work procedures conducted on critical, high-value operations.

The BPE technique has been used successfully in a different situation by the author of another chapter to estimate a 16,000-resource-hour maintenance procedure for hydroturbine maintenance in a governmental organization (see Chap. 15.5). In the absence of written instructions in this situation, a work breakdown structure was constructed with input from subject matter experts (SMEs). These SMEs then applied the BPE technique to that work breakdown structure. The sum of the estimates was within ±2 percent of the actual times experienced on the next occurrence of the hydroturbine maintenance. The aggregate accuracy of these estimates supported an improvement in job time of more than 10 percent.

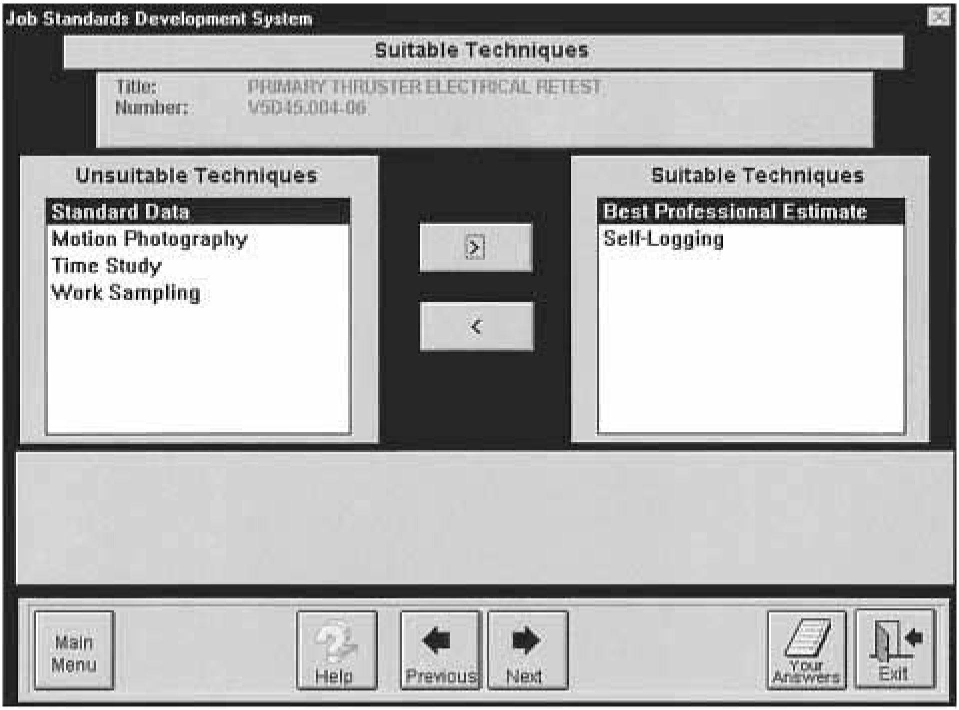
At the KSC, BPE estimates covered a variety of in-house and borrowed resources used to complete the maintenance instructions. These in-house and borrowed resources are shown in Table 15.1.2. Each maintenance instruction had an average of 12 jobs. Each job had an average of 52 steps. The written instructions provided a clear and detailed picture of the work breakdown structure of each maintenance instruction. Each maintenance instruction used an average of 250 hours of in-house labor for execution.

TABLE 15.1.2 In-House and Borrowed Resources Needed to Complete Maintenance

Instructions	
In-house labor categories	Borrowed resources
Direct labor	Camera
Engineer	Crane riggers
Quality	Fire and medical
Safety	Life support
Sampler	NASA quality
Technician	X-ray technician
Indirect labor	
Pad leader	
Supervisor	

At the detailed level, BPE was applied using an engineer and a technician as the SMEs. A facility manager remarked that the job time estimates generated with the technique were the best he had ever seen. And it was the first time some realized that certain jobs required the concurrent presence and successful performance of more than 10 other personnel. The application of BPE to existing detailed instructions measured 502 direct hours of work with 14.1 hours of SME time. The BPE produced 36 hours of time estimates per hour of SME time expended.

A follow-on development effort focused on developing an expert computer system that could be used by SMEs to make estimates without the intervention of an interviewer. The expert system is loaded with information about each step of each job of a maintenance instruction. The SME can then work through the entire instruction, as time is available, to estimate resource requirements and elapsed time to complete. Two screens from the expert system are shown in Figs. 15.1.5 and 15.1.6.



Job Standards Development System

Suitable Techniques

Title: PRIMARY THRUSTER ELECTRICAL RETEST
Number: V5D45.004-06

Unsuitable Techniques
- Standard Data
- Motion Photography
- Time Study
- Work Sampling

Suitable Techniques
- Best Professional Estimate
- Self-Logging

FIGURE 15.1.5 Suitable techniques based on user input.

Postal Service

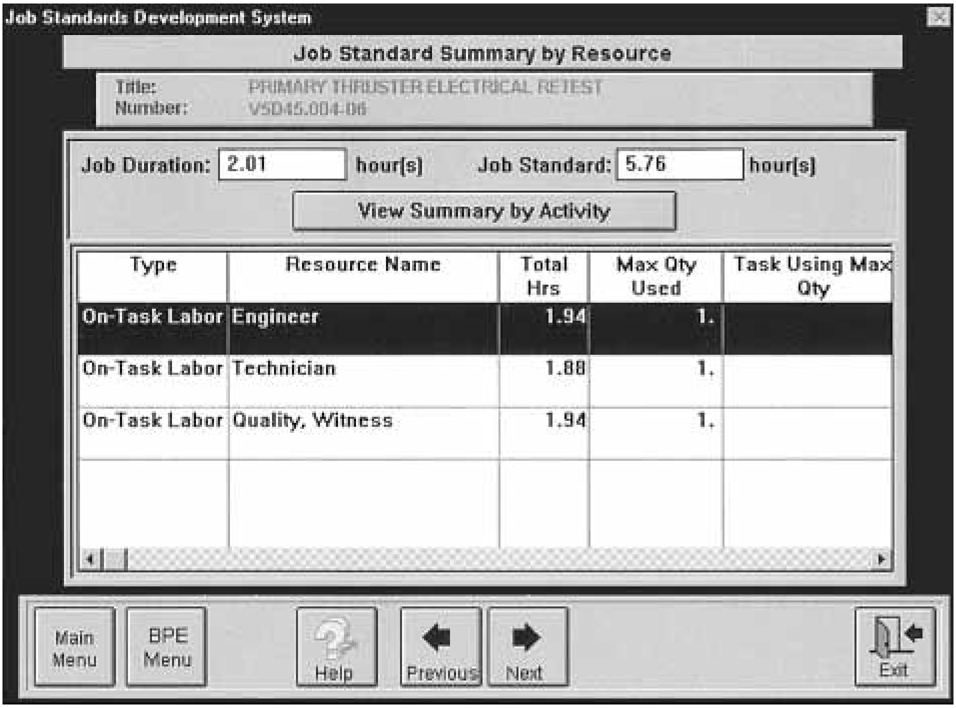
In government, the driving force is not always cost reduction. Rather, it is improved service, improved quality, or providing expanded service with the same workforce. Improvement is obtained more through working with people than changing processes. This is true even in bulk processing plants using considerable capital equipment. Some unions will work with management on the premise that they can control the outcome better if they are discussion participants from the beginning; other unions just say no.

Management approaches or styles come in different forms. Some will try to be harsh disciplinarians, some will do an inspired job of making improvements, and some will provide custodial service and keep things as they have been.

There is a sound, fundamental best method for doing things. The problem is that the method is often not followed. A case in point is an operation where 100 operators were studied.

- Fifteen of the operators produced 2000 pieces per hour.
- Sixty of the operators produced 1500 pieces per hour.
- Twenty-five of the operators produced 1000 pieces per hour.

The IE standard for the operation was calculated at 1700 pieces per hour. The reasons for substandard performance were:



Job Standards Development System

Job Standard Summary by Resource

Title: PRIMARY THRUSTER ELECTRICAL RETEST
Number: V5D45.004-06

Job Duration: 2.01 hour(s) Job Standard: 5.76 hour(s)

Type	Resource Name	Total Hrs	Max Qty Used	Task Using Max Qty
On-Task Labor	Engineer	1.94	1.	
On-Task Labor	Technician	1.88	1.	
On-Task Labor	Quality, Witness	1.94	1.	

FIGURE 15.1.6 Job standard summary by resource.

- Seventy percent resulted from operators using an incorrect method.
- Fifteen percent resulted from actions by upstream operators, which slowed work down.
- Fifteen percent resulted from the normal rejection rate being 1 percent, but machines were actually rejecting 10 percent.

It is the author's experience that the most successful improvements occur when unions get involved in the improvement process.

Video is a very helpful way to record what is actually going on in a plant. However, for video to be effective, it is best used with the understanding that management will not use the video for punitive purposes. Video can demonstrate good and bad methods. In one case, union representatives were surprised to see that:

Worker A. Working at a lower effort level with the correct method, produced 1500 pieces per hour.

Worker B. Working at twice the effort level, but with a poor method, produced 800 pieces per hour.

Experience of the authors suggests that simulation modeling can show supervisors and lead workers the advantages of improved work methods. This was shown by simulation involving both people and automated equipment performing parcel sorting.

Process flow charting has also been used with some success in analyzing and improving processes. It is best to assemble representatives of all different operations in a process together to construct a process flow chart. By studying the process flow chart, one can learn that when

INDUSTRIAL ENGINEERING IN GOVERNMENT

an upstream operator removes a piece of plastic scrap, this will save a downstream operator from having a time-consuming equipment jam. Using the process flow analysis, one process went from 30 percent up to 80 percent of standard, and a quality index also improved.

WAYS TO WORK WITH OR FOR THE U.S. FEDERAL GOVERNMENT

An IE graduate has considerable newfound knowledge ready to be applied somewhere, but may not be sure how IE fits in. The following will give some idea of what to expect in the government sector.

Typical Government Positions

Industrial engineering is a discipline that prepares an individual for a wide variety of assignments. An IE background qualifies a person for several government positions, some of which include:

- Management analyst
- Program analyst
- Budget analyst
- General engineer
- Operations research analyst

Typical IE Work in the Government

Work Measurement. One large agency uses methods time measurement (MTM) to develop work standards and formulate staffing levels for processing operations.

Cost-Benefit Analysis. New equipment projects typically have a cost-benefit analysis performed by an industrial engineer. These usually compare the current method with that proposed. Associated personnel savings should pay off the investment within three years.

Simulation Modeling. Process automation often requires simulation modeling to ensure proper staffing and scheduling so that the change will perform in the manner upon which cost justification was based. Simulation is also used to identify needed human resources support and training, as well as transition planning for phase-in.

Budgeting. The federal government is constantly planning many years into the future. The budget process has a long lead time due to the many management reviews within organizations. The Office of Management and Budget (OMB) reviews and approves the various department budgets. Congressional oversight committees review and approve agency budgets. As many as eight different oversight committees may review a budget request. Industrial engineers help by developing mathematical models that are used to predict staff requirements on the basis of planned output of the agency.

Project Planning. Gantt charts and program evaluation and review technique (PERT) charts are used throughout government for project planning and management. The industrial engineer helps to create the basic schedule and then works with line management to keep it up-to-date and to analyze the schedule for potential conflicts to be prevented.

Workload Planning. Balancing workload to staffing levels requires reliable data and accurate forecasting. Balancing is essential for an efficient operation. Examples of workload planning include:

- U.S. Department of Veterans Affairs (VA) hospital staffing under varying patient loads
- Postal Service staffing to meet fluctuating mail volume
- Truck, train, and airplane scheduling to meet fluctuating shipment patterns

Planning and Evaluation. Planning involves being able to analyze historical data, predict trends, identify potential problems, and then predict the changes required to solve possible expansion of project costs, additional staffing levels needed, and changes in funding estimates.

Evaluation requires that a project be reviewed critically by applying a methodical and logical approach to assess progress in meeting deadlines and to determine feasibility of implementing improvements.

Production Capability Assessment. Industrial engineers often visit contractors to assess the status of an acquisition, whether deliveries are on schedule, and what to do to improve the schedule. They will document findings and prepare written recommendations to management.

Source Evaluation Boards. Industrial engineers serve on source evaluation boards to evaluate quality assurance, delivery schedules, specification clarity, and to help with source evaluation. One organization in the U.S. Department of Defense (DoD) will, for example, evaluate all aspects of a weapon system cost. They provide cost models showing the effect of quantity variations on costs for use in acquisition strategy decisions. When a weapon system has become obsolete, strategies are formulated to facilitate the disposal of the systems. In monitoring programs, the following types of work are done:

- Schedule performance analysis
- Cost-variance analysis
- Earned-value analysis
- Acquisition analysis
- Contract proposal analysis

Further examples of IE work in the government can be found in *IE Solutions,* published by the Institute of Industrial Engineers in Norcross, Georgia. Their Web site is www.iienet.org.

Employment Information

As of September 1995, the latest available statistics, there were nearly 2000 individuals with positions classified as industrial engineers in government organizations. As of 1999, an industrial engineer with a Bachelor of Science degree entering the U.S. federal government service could expect a starting salary above $26,000. The top pay of a journeyman-level industrial engineer in 1999 is above $60,000 and the highest pay for an individual classified as an industrial engineer would be greater than $100,000 per year.

U.S. government job openings can be obtained by calling any of a number of U.S. Office of Personnel Management (OPM) service centers. The telephone number in Washington, D.C., is 202-606-2525. Another popular approach is to access the OPM Web site at www.opm.gov. In addition, the Institute of Industrial Engineers (IIE) may provide assistance through their Web site, www.iienet.org.

Private Consultants Working for the Government

Work in the government may be a stepping stone to working as a consultant or with a contractor that provides services to the government. While work with the government can be frustrating because of bureaucratic red tape, the challenges are great and the scope of problems is immense. The need for rational, IE-based management of government resources and programs is substantial and should be important to every taxpayer.

An alternative to working directly for the government is to work for one of the many firms that provide services and products to the government. Complex and demanding assignments are often outsourced rather than performed by in-house personnel. A starting place to search for management consulting firms is the Institute of Management Consultants (USA). Their web site is www.imcusa.org.

FUTURE TRENDS

Governments will continue to get bigger in absolute terms as the world economies grow. This trend will create bigger, more complex, and important problems to solve. At the same time, there will be political pressures to reduce the size of government. These pressures will create legislative support for IE work. These two facts should make interesting opportunities for industrial engineers to use their skills in government.

Independent consultants will provide increasingly more services to governments at all levels. Within governments, IE work may be done by differing job titles such as management analyst, budget analyst, or project manager. The industrial engineer will need to look beneath the surface to decide where the greatest opportunities lie.

Participation has always been an important ingredient of government IE consulting. The trend within industry to delegate decision making to teams is causing industry to develop team-oriented participative processes that will be quite useful in government. Consequently, the same IE techniques that work in private industry will work equally well in government. It will be easy to transfer skills from industry to government and back. The future is indeed bright for industrial engineers within governmental organizations.

BIOGRAPHIES

Herbert Harris is President of H.J. Harris & Associates in Baltimore, Maryland. His firm provides IE consulting to the U.S. federal government. He holds a Bachelor of Science in Industrial Engineering from the University of Alabama and a Master's of Science in Business Administration from the NYSUB. His consulting work is with various branches of the government. His prior employment was with the U.S. Departments of Agriculture, the Veterans Administration, and the U.S. Post Office.

Rudolf Mosnik is a Principal with ROI Consultants of Zurich, Switzerland. Dr. Mosnik is managing director of ROI's operations in Austria. He has a Dr.Jur. from the University of Vienna. His consulting practice involves banking and legal court systems. In private industry, Dr. Mosnik worked in personnel and materials management in the paper, machinery, and ball bearing industries.

Joseph Redding is one of the senior vice presidents with H. B. Maynard and Company, Inc., Industrial Engineering Consultants. He holds a Bachelor of Science degree in Electrical Engineering and a Master's of Science degree in Industrial Administration from Carnegie Mellon

University. He has governmental consulting experience with the U.S. Navy, U.S. Mint, and the U.S. Postal Service.

Neal Schmeidler is president of Omni Engineering and Technology in McLean, Virginia. His firm provides IE consultation to the U.S. federal government. He holds a Bachelor of Science in Mathematics from Fort Hays State University and a Master's of Science in Industrial Engineering from Kansas State University. His government clients include the Federal Aviation Administration (FAA), the National Aeronautic and Space Administration (NASA), and the U.S. Army.

Thomas Seidel is a cofounder of ROI Consultants of Zurich, Switzerland. He holds a Ph.D in Chemistry from the Federal Institute of Technology, Zurich. He has completed additional studies in IE. His work experience includes both technical and managerial positions. His consulting work covers the fields of general management, strategy, and restructuring. For the past eight years, he has focused in the field of public administration in Switzerland, Germany, and Austria.

Source: MAYNARD'S INDUSTRIAL ENGINEERING HANDBOOK

CHAPTER 15.2

FACILITIES PLANNING AND LABOR MANAGEMENT IN THE FOOD SERVICE INDUSTRY

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Competition in the fast growing food service sector has fostered a need and interest in systematically engineered solutions that drive profitability while improving guest satisfaction. Industrial engineering methods and techniques are ideally suited to developing these solutions. This chapter describes systematic, time-tested approaches to facilities planning and labor management in this business sector that simultaneously improve the cost structure of the retail unit and increase the value received by the guest. These approaches have been developed through systematic application of engineering techniques and have significantly benefited from practical experiences. The systematic processes described have been primarily applied to chains of restaurants; however, the process has been successful, in a simplified form, when applied to individual restaurants.

BACKGROUND

The food service industry has a number of characteristics that must be given careful consideration when applying an engineered approach to its problems.

- Most design issues will be impacted by customer behavior, which is generally random in nature. This differs dramatically from most manufacturing systems where the customer is never involved in the production process. Some food service chain restaurants even encourage customers to intervene in the assembly process by customizing their order at the time of order placement (like condiments for sandwiches).
- The processes that the customer follows must also be analyzed and be an integral part of any design or system. This includes customer flows, ordering processes, queuing, receiving

food products, sitting, eating, paying, and leaving. Even if an industrial engineer in manufacturing considers the customer as the ultimate beneficiary of the design effort, it is at best a remote connection, while in the restaurant industry it is very direct.

- Solutions proposed may be implemented in numerous facilities in many geographical locations, giving the designer little control over the operational execution of the restaurant solutions. Robust, simple, and effective solutions are more likely to have an impact than complex, optimal solutions.
- This is an industry with complex quantitative problems related to production processes that are typically not very sophisticated technologically. The complexity of the quantitative problems originates in the random behavior of customers interacting with the system and the variance introduced by multiple locations of a chain. The processes—cooking and assembling food—are intuitively simple. Most processes have direct correlation to those that could be performed at a consumer's home, the main difference being the size, capacity, and features available in commercial equipment. Some food service operators emphasize "home cooking" as a feature, implying that the processes used are similar to those used at home.

It is important to note that the scope of application of the methodology described is focused on existing, viable food service concepts or chains that require optimization of their operations. It is assumed that the nature of the products and services offered has been predefined such that they can be considered design requirements. As a result of application of the techniques described, it is not typical to expect that the types and mix of products and services offered will change dramatically. In some exceptional cases, products that become obstacles to optimizing the overall operation could be eliminated from a concept offering to optimize resource utilization and customer satisfaction. It is frequently exactly the opposite, as operators strive to increase variety to improve sales and guest satisfaction.

Industrial engineers are likely to play an increasingly significant role in the food service sector. Currently they are focused on operations support activities but through process analysis and cost control skills are uniquely positioned to spearhead dramatic process improvement initiatives to reduce costs and simultaneously improve guest satisfaction.

FOOD SERVICE FACILITIES PLANNING

The underlying techniques and principles applied in food service facilities planning do not differ significantly from those used in planning any generic production, warehousing, or distribution facility. To that effect, we will focus primarily on the particulars of application of the techniques and principles of the industrial engineering profession to the food service facilities planning problem.

Objectives of Food Service Facilities Planning

Reduction of Operating Costs. A well-engineered food service facility should minimize operating costs. Labor typically accounts for between 20 and 40 percent of sales, while food and paper goods account for between 25 and 45 percent of sales. Utilities and rent are typically the remaining largest cost components after food and labor. The food service facility plan, and underlying processes, should therefore

- Strive to reduce labor costs by eliminating activities that add no value.
- Reduce food waste by providing optimal cooking and assembly processes.
- Specify equipment and workstations that reduce overall energy consumption.
- Use the smallest footprint that will satisfy the service demands to minimize rent or building depreciation.

Reduction of Capital Investments. The use of appropriate engineering techniques will significantly reduce the expenditures on equipment and reduce the size of the equipment, thereby greatly reducing the size of the facility required to service a certain demand that should reduce the total capital investment. In some cases, equipment that is sophisticated in nature but does not provide significant benefits will be eliminated to achieve dramatically reduced capital investment. This significantly impacts the use of automation (or any other productivity-enhancing investments) in the food service sector because the benefits are generally more limited, and more difficult to quantify, than in manufacturing. Food service facilities are used at the peak of their capacity during meal periods and are operating at their peak level for as little as one hour a day on the day of the week with the highest volume. The impact of automation in food service is therefore reduced because it is profitable only over short periods of time, while in manufacturing automation can be made profitable around the clock. In summary, as the engineer plans the food service facility, a high priority should be placed on reducing the capital investment and focusing on relatively smaller investments when pursuing productivity improvement opportunities. The smaller the investment, the quicker a chain can develop profitably.

Improved Service and Value Delivered to Guest. There are a number of factors that contribute to improved service and value, and they are usually measured in terms of customer satisfaction surveys. Items to consider are the temperature and quality of the food served to the guest, as well as the speed and convenience with which they are served. Due consideration should also be given to the availability of different modes of service (dine in, take out, delivery, drive through), and the resulting environment. For example, a powerful blender may be necessary in a juice store for speed of service; however, the added noise will adversely impact the environment. All of the aforementioned factors will impact how the customer perceives the value received.

Access to Real Estate Opportunities. In addition to reducing the capital investment and the size of the facility needed, an engineered solution can tailor the facility to different demand patterns and to different levels of sale volumes. For instance, for an operator that wants his or her retail location to be no more than 21 ft in width, a facility may be matched to that given real estate constraint.

Underlying Engineering Process

The following is a brief and summarized version of the engineering process—a process used as a basis to develop the food service facilities plan.

1. *Research, observe, and analyze.* This includes any types of observations through work sampling, research of the industry, research of the technologies available, and any analysis techniques that include work measurement, capacity analysis, computer simulation analysis, and operations research analysis.
2. *Identify strengths, weaknesses, opportunities, threats.* Once the research is complete, the strengths, weaknesses, opportunities, and threats (SWOT) of a given production system are identified.
3. *Research and develop alternatives.* Once the SWOT analysis is completed, brainstorming or systematic alternative development techniques can be applied to determine new feasible alternatives to the opportunities and threats encountered.
4. *Evaluate alternatives.* Alternatives are evaluated using work measurement, computer simulation, operations research, value engineering, economic analysis, and prototype testing.
5. *Implement solutions.* After the best alternatives have been selected, solutions are implemented.

Food Service Facilities Planning Process

Business Data Analysis. Business data analysis is performed in the food service industry for a variety of parameters. The most important ones are to relate the macro performance measures of a restaurant chain and each one of the variables that could impact that performance. Specifically, it is of great interest to know how profitability, sales, and customer satisfaction correlate to a number of variables. Those variables could include labor cost, food cost, utilities, size and type of the facilities, and also the types of products offered. This analysis could typically be a correlation analysis between all these variables to see if they are tightly correlated or not. For example, if we find that labor is tightly correlated to sales, we may be able to state that a chain tightly controls its labor as opposed to other chains where the correlation is not tight. The same can be said for food costs. It may also be possible to find occasions where there is significant profitability tied to the footprint of the facilities that are being analyzed. Therefore, we could infer that a bigger facility could reflect in higher sales. However, in many cases analyzed, the footprint of the facility is not closely correlated with the total sales and profitability, indicating that there is a mismatch between the optimal resource requirements for a food service facility and actual resource requirements. The analyses between these variables can indicate whether there are some interesting correlations that are worth investigating further and, most important, considering as a factor to drive the facility plan. Figure 15.2.1 is an example graph plotting labor costs against sales for further analysis.

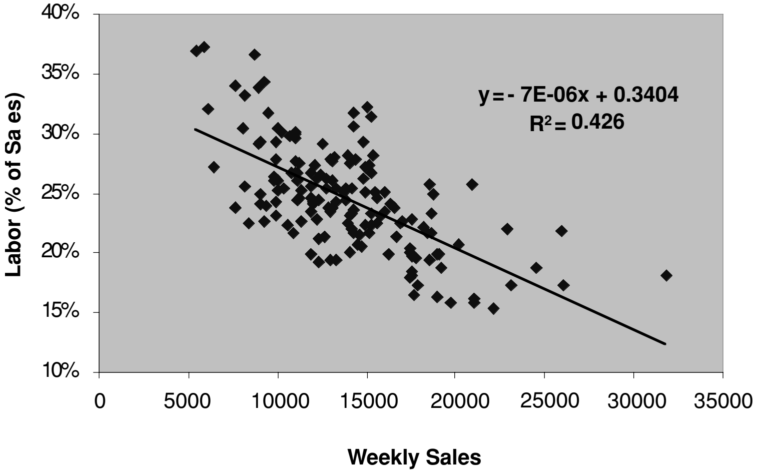

FIGURE 15.2.1 Labor cost (as percent of sales) plotted against sales. This chart shows low correlation of labor costs to sales, which reveals an opportunity to control costs better.

Industry Benchmarking. It is important to compare certain facility performance parameters such as speed of service, customer satisfaction, food costs as a percent of sales, and labor costs as a percent of sales against industry benchmarks. As was mentioned previously, labor costs are typically between 20 to 40 percent of sales. If a chain were outside of that range, it would be clear that they would have an excellent labor cost structure if they were below 20 percent, and a very significant problem if it were over 40 percent.

Industry Segment Trends. For a given type of food service chain, it would be useful to explore whether they are following some of the typical trends of that segment. This exercise depends extensively on a good knowledge of current trends and access to research on leading edge developments. For example, if it were a bagel concept focused on full-waited service, it could be stated that this is not typical of what the rest of the industry is doing in that segment. Another example would be a blended juice vendor that does not use dispensing for the juices. That would be different from what is common for most other juice vendors. So, industry segment trends are based on general information available to the public and general information available in different studies. It is important to make those comparisons to see where a particular operator stands.

Food Service Facility Sampling Study. This study is conducted to ensure that the engineer observes the operations in a systematic fashion and that a thorough understanding of the critical parameters of the operation is understood. A number of factors are observed when performing a restaurant sampling study. Specifically, utilization of resources such as labor, equipment, workstations, and queuing areas are tracked against the performance of the system. The performance of the system is measured in a variety of ways, including the number of guests that are transacted, the sales that are transacted, and the quality of guest service. Typically, to track the quality of guest service, some very simple and obvious parameters are defined that are likely to be correlated to customer satisfaction—for example, when an order is taken, whether the customer is greeted and thanked, or when the order is delivered, whether the customer is thanked. Measurements correlated to customer satisfaction could also include food temperature or food portioning. It is critical that the engineers understand from operations management which parameters are correlated to customer satisfaction before the study begins to ensure that those parameters are duly tracked.

One of the most important parameters correlated to customer satisfaction is the speed in which the guest is served. We highly recommend tracking it in any restaurant sampling study because it is a good indicator of operational execution, as well as being a measure of customer satisfaction. This aspect is so important that, in most studies, the components of customer delays are studied as well, such as queuing, register, food assembly, and pickup times.

In summary, there are a number of variables that can be observed in a systematic fashion over a significant amount of time in large geographic regions to understand the opportunities in a given restaurant chain. The utilization of resources is analyzed against the performance of the food service facility from both operational and consumer perspectives.

Figure 15.2.2 shows an example of a data collection form used for food service facility work sampling; Fig. 15.2.3 shows one of the resulting outputs.

SWOT Analysis Summary. At the end of the restaurant sampling study and given that business data analysis, industry benchmarking, and industry segment trends have been performed, the engineer develops a SWOT analysis summary. This summary report indicates where the strengths, weaknesses, opportunities and threats are defined for the particular restaurant operator. These findings will indicate the basis for further work and will focus the engineer on the next steps so that he or she can proceed in identifying and refining alternative process improvement ideas. The opportunities predominantly focus on reducing resources when utilization is low and eliminating bottlenecks when resource utilization is high.

Design Basis Analysis. The design basis analysis is performed to understand how higher level business objectives such as sales and profitability, correlate to critical food service facility system variables to drive the food service facility plan. Critical variables may include peak demand hours or days for a certain product such as sandwiches or salads. This is approached in a top-down manner in which a desired yearly sales objective is established for a given facility design. This objective could be established by analyzing percentiles of existing stores that meet certain sales targets; for example, it is typical to establish a facility plan for 50, 80, and possibly 98 sales percentile stores, representing low, medium, and high volume sales solutions, respectively. For example, the 50 percentile sales level would be such that 50 percent of the stores in the system are under that sales level. And starting from that point, a yearly sales number, it is necessary to find ways of getting down to peak hourly or

Store # 123	Study conducted for:	CLIENT XYZ	8/14/97 Page _2_ of _22_

DAILY INFORMATION	Sales: $5,156	Transactions:	705	Allowed Hours:	108
	Check Avg.: $7.31	Items/Check:	3.4	Actual Hours:	121

OBSERVATION #	1	2	3	4	5
Total Staff	16	15(*)	16		
Sales (30 min)	$890	$750	$750		
Trans (30 min)	150	129	129		
TIME OF DAY	12:30 PM	12:36 PM	12:42 PM		

GUEST DELAYS (minutes—continuous)

Product Type	Grill-Fry-Other	Grill-Fry-Other	Grill-Fry-Other	Grill-Fry-Other	Grill-Fry-Other
Register Queue	2:31	0:42	3:45		
Register Time	3:25	1:21	4:59		
Pickup Time	6:21	8:34	6:21		
Items per Check	3	5	2		
Check Amt	$8.91	$15.21	$4.21		
GUEST SATISFACTION	Y/N	Y/N	Y/N	Y/N	Y/N
Guest Greeted	Y	Y	Y		
Guest Thanked	Y	N	Y		
Confirm at Pickup	Y	Y	N		
WORK SAMPLE	CRW/MG	CRW/MG	CRW/MG	CRW/MG	CRW/MG
Register	AAI/	AAA/	AII/	/	/
Expedite	IW/	A/	W/	/	/
Bussing	W/	I/W	WA/	/	/
Assembly Line 1 (Start Order)	AWA/	AIW/	AII/	/	/
Assembly Line 2 (Finish Order)	I/	AA/	A/	/	/
Food Cooking Line 3	/	W/	AA/	/	/
Food Prep	ATI/	AI/	/	/	/
Cleaning	AI/	A/	WWA/W	/	/
Administration	/A	/	/	/	/
	/	/	/	/	/
	/	/	/	/	/

BOTTLENECKS/Capacity		Utilization	Utilization	Utilization	Utilization	Utilization
Registers (Each)	4	2	3	2		
Broiler (Feet)	6	2.5	1.5	4		
Griddle (Feet)	4	1.5	0	3		
Oven (Shelves)	5	1	0	4		

NOTES: A—Active T—Talking W—Walking I—Idle
(*) One Employee on Break
Observations: Expedite station not ergonomic, excessive bends.
Too many pans in assembly lines, affecting length of reach, reducing efficiency.

FIGURE 15.2.2 Example of restaurant work sampling data collection form.

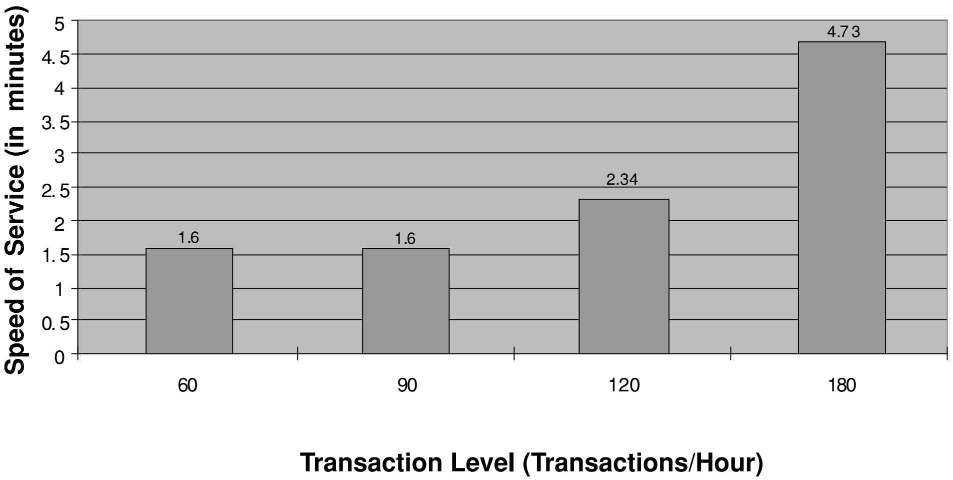

FIGURE 15.2.3 Example of restaurant sampling analysis output. This graph shows deteriorating speed of service as hourly transaction levels grow. Although this is typical in the food service industry, a well-designed facility should provide similar speed of service (SOS) over the full range of transaction levels used as a design basis.

half-hourly demand, or requirements of the critical variables. That could be completed as follows:

- Annual sales data is collected from a significant number (*n*) of locations.
- For the same *n* locations, weekly sales are collected over an entire year to establish the peak weekly sales that correspond to given annual sales. In this way a tight correlation can be established between annual sales and peak weekly sales.
- For the same *n* locations, daily sales data can be collected to significantly correlate weekly sales to peak daily sales.
- For the same *n* locations, critical variables or drivers for a peak hour or half-hour within a day can be collected to establish a tight correlation between peak daily sales data and critical hourly or half-hourly data.
- Based on the *n* locations, functions are developed that provide hourly or half-hourly design parameters given desired annual or weekly sales input. In this way the values of critical variables or drivers such as daily, hourly, or half-hourly sales, transactions, guest counts, breakfasts, lunches, or dinners (or even a specific menu item) that drive the facility plan will be firmly quantified.

Table 15.2.1 indicates the relationship between weekly transactions/weekly sales and other variables that establish the design basis for a food service facility.

Capacity Analysis and Requirements. The capacity analysis will use the critical variables established in the design basis analysis as a driver of the capacity of each one of the resources in the facility (e.g., floor space, equipment, workstations, labor, etc.). One of the characteristics of the food service industry is that resources have to be significantly underutilized to be able to provide a level of service that is acceptable. It is common to observe some pieces of equipment utilized at 50 to 60 percent; many pieces of equipment in a food service facility may be utilized at under 20 percent simply because they are the minimum size manufactured for that particular type of equipment.

The typical formula for the calculation of the equipment or workstation capacity would be as follows:

TABLE 15.2.1 Example of Output from a Design Basis Analysis

Percentile existing stores	Weekly trans	Weekly sales	Peak hr trans	Peak lunch hr trans	Peak dinner hr trans	Peak hour drink	Peak hour POS	Peak hour sandwich
50	3000	$15,000	111	97	90	95	97	84
80	4500	$22,000	141	128	128	125	128	104
99	6000	$29,000	171	159	165	155	165	123

Note: For different levels of critical design drivers (weekly sales and transactions), peak design variables are established, which is the first step in quantifying the resources required.

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$$\text{Capacity (design parameter)} = \text{units of resource} \times \text{unit capacity (driver/hour)} \times \text{ratio (design parameter/driver)} \times \text{utilization}$$

The formula therefore applied to the calculation of equipment or workstation requirements (in units) would be as follows:

$$\text{Units of resource} = \frac{\text{required capacity (design parameter)}}{\text{unit capacity (driver/hour)} \times \text{ratio (design parameter/driver)} \times \text{utilization}}$$

The capacity needs to be calculated in terms of the design parameters determined by the operator, such as sales or transactions per week or year. The ratio between design parameters and drivers (such as pizza pies per hour) of the capacity of a given resource is an output from the design basis analysis. The utilization is set at a level that would allow the equipment or workstation to provide an appropriate level of service to the customer of the food service facility. A high utilization has a negative impact on speed of service and generates queues at the resources in question. This utilization level is established by computer simulation, work sampling, or by professional estimate. Table 15.2.2 shows the output of a typical capacity analysis.

During the process of performing a capacity analysis, a great deal of attention needs to be placed on the feedback of experienced operators. There is always a theoretical solution that could represent or model some of the very complex behaviors that include interaction with customers and interaction with different types of operators. However, the great variety of pieces of equipment in a food service facility, coupled with many behaviors that are seldom seen by the engineer because they occur rather randomly and infrequently, require that the engineer pay close attention to experienced operator feedback. A good example of this is in the production of waffles. Some food service concepts are very successful in selling significant volumes of waffles, while some sell significantly less. Those that sell few waffles have a particular problem with the deployment of waffle irons. If the engineer analyzes the use of waffle irons in chains that do not have significant sales of those products, it could be concluded that the utilization of waffle irons, when using two or three waffle irons, would be less than 10 percent. The engineer might contemplate proposing the use of only one waffle iron for the food service facility. However, the nature of orders of waffles may preclude that. For example, it may be that most orders of waffles come in multiples of two, three, or four and are typically ordered by larger parties; if only one waffle iron were available by the time the second waffle in an order is cooked, the first waffle would be cold. In this particular example, overall low utilization is a requirement to offer an effective product despite a capacity analysis that would have indicated that one piece of equipment would have been sufficient. Listening to operators can save the engineer from costly and extended periods of observation that would be required to observe random events that occur very infrequently.

Workstation and Process Analysis. This analysis includes an understanding of all products and ingredients that enter the workstation, all the products that exit the workstation, and all the equipment and tools that are required to process the items within the workstation. The products that exit the workstation must include all the waste and trash that is produced at a workstation in the process. The process analysis would include traditional process or work flow diagrams together with the times to execute the different processes or elements of those processes. It would also include different types of work measurement techniques from stopwatch observation to predetermined time standards to establish the work content of the different processes. Figure 15.2.4 shows an example of a process analysis form for an operation of assembling sandwiches.

TABLE 15.2.2 Example of Capacity Analysis Output

Capacity analysis summary for: XYZ Prototype Design							
Rev m/d/yy	Percentile Store Weekly Sales	95% $35,000.00	80% $30,000.00	65% $25,000.00	50% $22,000.00	35% $21,000.00	20% $19,000.00
Equipment/station	Description						
Cold Prep Stations	1 person station	1	1	1	1	1	1
Ice Cream Station	1400 oz/hr Single Barrel	198 oz/hr	176 oz/hr	174 oz/hr	160 oz/hr	152 oz/hr	152 oz/hr
Ice Cream Blenders	Brand Y	1	1	1	1	1	1
Fryers	Brand Z 15″ 70 lb/hr	1	1	1	1	1	1
Hot Prep Station:							
40-Quart Kettle	Brand X—Model xx	2	2	2	2	2	2
Rice Cooker	Brand C—10.5 quart	1	1	1	1	1	1
Hot Water Dispenser	Brand D—7 Gal/Hr	6 gal/hr	6 gal/hr	4.5 gal/hr	4.5 gal/hr	3.5 gal/hr	3.5 gal/hr
Ice Machine	Bin size/Ice Maker*	400/650	400/600	350/500	350/500	300/450	300/450
DT Drink Stations	8 head dispenser	1	1	1	1	1	1
Product HH Prep Stations	1 person station	1	1	1	1	1	1
Product HH Cut Station	1 person station	1	1	1	1	1	1
Hot Hold Cabinet:							
Hot Food Shelves	7″ shelves	1.75	1.5	1.5	1.25	1.25	1
Ingredient Shelves	3.5″ shelves	2	2	1.75	1.75	1.5	1.5
	Half Height Cabinet	0	0	0	2	2	1
	Full Height Cabinet	1	1	1	0	0	0
Tables		25	19	15	13	11	10
Seats		70	55	50	45	40	35
Ovens							
Combi:							
Combi A	Brand E	2	2	1	1	1	1
Combi B	Brand E	0	0	1	1	1	1
Final Processing	Brand F Charbroiler	4 foot	4 foot	3 foot	3 foot	3 foot	3 foot

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TABLE 15.2.2 Example of Capacity Analysis Output (*Continued*)

Prefinished Product HH Hold	3.5″ shelves	10	10	7	7	7	7
	Full Height Cabinet	1	1	0	0	0	0
	Half Height Cabinet	0	0	1	1	1	1
Finished Product HH Hold	Holding Grill	2 foot	2 foot	2 foot	2 foot	2 foot	2 foot
Impingement:							
Impingement—36	Brand H	0	0	0	0	0	0
Impingement—54	Brand H	0	0	1	1	1	1
Impingement—72	Brand H	1	1	0	0	0	0
Finish Grill	Brand G	4 foot	4 foot	3 foot	3 foot	3 foot	3 foot
Prefinished Product HH Hold	3.5″ shelves	9	9	7	7	7	7
	Full Height Cabinet	1	1	0	0	0	0
	Half Height Cabinet	0	0	1	1	1	1
Finished Product HH Hold	Holding Grill	2 foot	2 foot	2 foot	2 foot	2 foot	2 foot

Note: The three prototype design levels are shaded in gray for 20, 50, and 95 percentile stores. From the information presented, it is clear that there is virtually no difference between the 80 and 95 percentile stores (other than seats and tables); therefore, it makes sense to build the 95 percentile store whenever volume forecasts are above the 50 percentile level.

Equipment and Process Research and Development. This step would include any engineering to determine the appropriateness of equipment currently in use by the concept and to research alternatives available. This research and development effort must often include publishing a functional specification to prospective suppliers to solicit alternatives. The functional specification would describe (1) the state of the finished menu item or ingredient, (2) the capacities required per day or peak hour, (3) the mean time between failure of critical components, (4) the machine controls, and (5) the required health and safety standards compliance. Once supplier responses are evaluated, a sequential process of testing must begin. This process begins with simple feasibility testing and ends with on-site testing for many units to establish reliability and ease of use.

Development of Alternatives. The development of alternatives typically consists of summarizing all the information developed to this point, presenting it to a group of operators, and applying brainstorming techniques to develop alternatives. One very important factor in this brainstorming technique is that there is a systematic approach to ensure that all the possible variations or solutions are explored. We take an approach of verifying whether the processes, the products, and the modes of delivery are more or less integrated. This will ensure that we get a significant number of alternatives that will likely include most of the viable solutions. A systematic framework is used for developing workstation and facility alternatives to complement any ideation process. Essentially, three process variables determine the design of a food service facility: (1) product (e.g., hamburgers, french fries), (2) process (e.g., cut bread, add cheese), and (3) mode of service (e.g., drive through, dine in). The degree to which each of these variables is integrated will determine the design of the restaurant. For each of the process variables it is necessary to define three levels of integration: high, medium, and low. High and low integration are defined as extremes. Medium integration is simply anything in between. The definition for the level of integration of each variable is as follows:

	Process Flow Analysis Form													
	Task Type:	ASSEMBLE		Project:	XXXX									
	Mode:	DINEIN		Location:	SAN DIEGO					Page	_____	of	_____	
	Work Station:	ASSEMBLE		Observer:	DC									
	Position:	GRILL		Date:	8/12/98	Unit:				Professional Estimate			Avg (min)	
				Yield:	1	EA				0.75	0.70	0.750	0.73	
Task ID	Task Action	Task Description	Task Modifier	Task Application	Concept Task	Work Standard Time (min)								
2123	ASSEMBLE	SANDWICH			ASSEMBLE STEAK SWCH	0.79								
EL#[1]	Action[2]	Object[3]	From[4]	To[5]	Tool[6]	Classification[8]	Detail[9]	Distance[7]	Count[11]	Freq[12]	Simo[13]	Flag	Comments[15]	Total Work Standard[16]
1	READ	MONITOR				1	1	1	1	1				0.009
2	WALK		ASSEMBLY	REACH IN		1	1	1	5	1				0.056
3	OPEN	DOOR				1	1	2	1	1				0.027
4	GET & PLACE	PREPORTION MEAT MIX	SHELF	GRILL		2	1	2	1	1				0.027
5	WALK		REACH IN	GRILL		1	1	1	4	1				0.045
6	ACTIVATE	TIMER				1	1	1	1	1				0.006
7	WALK		GRILL	BREAD SHELF		1	1	1	3	1				0.034
8	GET & PLACE	BREAD	SHELF	TOASTER		1	1	1	1	1				0.018
9	POUR	BUTTER/OIL	BOTTLE	BREAD		1	2	1	1	1				0.035
10	WALK		BREAD SHELF	TOASTER		1	1	1	3	1				0.034
11	PUSH	PADDLE	IN	OUT		1	1	2	1	1				0.021
12	PULL	PADDLE	OUT	IN		1	1	1	1	1				0.012
13	ACTIVATE	BUTTON				1	1	1	2	3				0.036
14	WALK		TOASTER	GRILL		1	1	1	2	1				0.023
15	FLIP	MEAT MIX				1	2	1	1	1				0.042
16	PUSH	PADDLE	IN	OUT		1	1	1	1	1				0.012
17	GET & PLACE	BREAD				1	2	1	1	1				0.018
18	PULL	PADDLE	OUT	IN		1	1	1	1	1				0.012
19	WALK		TOASTER	ASSEMBLY		1	1	1	2	1				0.023
20	ASSEMBLE SIMO	CHEESE	PAN	BUN		2	2	1	1	1				0.024
21	PLACE	CHEESE	PAN	BUN		2	1	2	1	1				0.024
22	WALK		ASSEMBLY	GRILL		1	1	1	2	1				0.023
23	SCOOP	MEAT MIX				1	2	1	1	1				0.036
24	WALK		GRILL	ASSEMBLY		1	1	1	3	1				0.034
25	ASSEMBLE SIMO	CHEESE				2	2	1	2	1				0.048
26	GET & PLACE	BUN HALF	TRAY	BUN		1	3	1	1	1				0.024
27	ASSEMBLE SIMO	WRAP & SANDWICH	TRAY	COUNTER		1	1	1	1	1				0.018
28	WRAP	SANDWICH				1	1	1	5	1				0.036
29	GET & PLACE	SANDWICH	COUNTER	HANDOFF		1	2	3	1	1				0.036
														0.791

FIGURE 15.2.4 Example of process analysis form.

Product

- High product integration: All products or family of products follow one process flow.
- Medium product integration: Some products or families of products follow different process flows.
- Low product integration: Every product or family of products follows a different process flow.

Process

- High process integration: All processes, or family of processes, are performed in one station.
- Medium product integration: Some processes, or family of processes, are performed in different stations.
- Low product integration: Every process, or family of processes, is performed at different stations.

In practical terms, high process integration is when all the process is executed by one operator and low process integration is when a process is executed by up to four operators. When more than four operators are used in a serial fashion to execute a process, utilization (and thus efficiency) decreases dramatically due to dependencies in highly random processes that create significant temporary imbalances. If the process is highly variable in nature, it should not be executed by more than three operators.

Mode of Service

- High mode integration: All modes of service follow one process flow.
- Medium mode integration: Some modes of service follow different process flows.
- Low mode integration: Every mode of service follows a different process flow.

This approach for developing alternatives yields, at a minimum, an opportunity to ensure that all combinations of integration have been explored during an ideation process. A total of 27 combinations of integration are possible through this approach. If alternatives have not been developed for one or some of the combinations, the ideation process can be continued or forced until this happens or until it is determined that the combination is not feasible.

Using a pizza concept as an example, all pizza types (products) can be prepared on one line for high integration, or each pizza type (product) can be prepared at different stations for low product integration. An individual pizza-topping station would be an example of high process integration where all ingredients are added at one place. Now, if the pizzas were assembled at several stations where the sauce was added at the first station, the meats added at the second, and the vegetables and cheese added at the third, then this situation would be an example of low process integration. Additionally, if the pizza concept had eat in, take out, and delivery modes and each mode had its own assembly line, then this situation would be an example of low mode integration, while if all modes were assembled on one line, that would represent high integration. By exploring the possibilities of each of these variables, we can be confident that most process alternatives are explored, thereby giving us the best chance to find an optimal solution.

Documentation of Alternatives. All the alternatives can then be documented in sketches, process flows, and eventually documented in detailed plans, including detailed plans of workstations and layouts that will be documented on a computer-aided design (CAD) system.

Evaluation of Alternatives. A number of techniques are typically applied to evaluate alternatives:

- Work measurement
- Computer simulation

- Capacity analysis
- Energy analysis
- Speed of service and queuing analysis
- Consumer surveys
- Economic analysis
- Qualitative factors

Essentially, the engineer's function is to quantitatively evaluate the performance of the food service facility system in terms of economics and guest experience. In addition, it is important to pursue systematic reviews of the alternatives to gain feedback from operations and other internal experts. These evaluation techniques allow the engineer to make thorough recommendations regarding the preferred solutions.

Document and Incorporate Changes Resulting from Evaluation. At this point, after extensive evaluation, some modifications to the workstations, equipment, or layouts may be required. Some alternatives may be considered to have the highest probability of success with two, three, or four of them being considered front-runners. Detailed evaluation of the restaurant system's performance would yield opportunities to improve the food service facility plans. This is the time to incorporate these improvements resulting from the evaluation and document them in detailed food service facility plans.

Mock-up Testing. After all the possible technical aspects have been addressed, all the analytical techniques have been applied, and all the design techniques have been implemented, it is time to test the most important or potentially most successful alternatives in a real, live-test environment. To this end, a mock-up of a food service facility is developed with a variety of low-cost materials; for example, wooden assembly lines or workstations can be used along with actual equipment that is available from other food service operations or from suppliers. The objective of the test is to set up a food service operation as if it were a real-life location in which all the pieces of equipment, all the operators, and all the flow of ingredients and food to the customer would be reproduced. Even though the customer is not there, it is possible to simulate their presence by understanding some of their most common behaviors: the time it takes to order, the time it takes to cash, the time it takes to pick up an order, how long it takes to sit down. The idea is to take the theory that has been developed and incorporated into facility plans and take it one step further before it is exposed to real customers. The real customer will be a huge part of the design; however, at this point the customer is not involved, but at least the operation is being prepared to a point where it can be as ready as possible for exposure to customers. The mock-up testing could consist of several runs of approximately 20 to 30 minutes each at peak volume capacities. Several metrics of system performance should be tracked during a test of this nature. The first would be throughput measured in terms of guests, transactions, and sales. Speed of service, the time it takes the consumer to get the products after they have placed the order, is also important. Another item that is measured is temperature and presentation of the food. It would be very easy to engineer a system that can produce food very rapidly and efficiently; however, it may not be at the right temperature nor presented in an acceptable manner.

Document and Incorporate Changes Resulting from Mock-up Testing. All the changes determined to be worthwhile for implementation from the mock-up tests would be incorporated at this time. This is a final opportunity before building a real facility to add feedback from operators and executives, plus performance feedback from the actual operation of the mock-up test.

Implement Solution in Test Food Service Facilities and Document Changes to Facility Plans. Construction documents are developed and the restaurant facility plan is implemented in a test restaurant. It is yet another opportunity to observe the impact of the solution.

Often, still more issues need to be addressed and they will be incorporated and documented before systemwide implementation.

Systemwide Implementation. Systemwide implementation consists of taking the final restaurant facility plans to the whole system. This is done in several phases. In the first phase, the final solution is implemented in a market that would include 10 to 15 restaurants. At this point, the goal is not to test whether the solution has been perfected but to start developing training materials that will facilitate the development of a significant implementation plan. Once the initial development of restaurants is complete to test training systems and implementation procedures, then the food service facility plans are ready for nationwide deployment.

RESTAURANT LABOR MANAGEMENT SYSTEMS

Objectives

Reduction of Labor Costs. One of the primary objectives of labor management systems is to control labor costs. Labor costs are the largest controllable cost in a restaurant chain. To that effect, there are a number of issues that need to be controlled regarding labor. First, the total number of hours used in a given restaurant has to be kept to a minimum. However, this has to be combined with the hourly rate that is paid to each of the operators. It may be that a slightly more skilled operator could be significantly more productive and reduce the overall cost of labor to the restaurant. It is a fallacy to try to control exclusively the total hours in a restaurant or control only the average wage paid in a restaurant. The combination of both has to be looked at in a detailed fashion. Consideration has to be given also to the different labor costs in different regions of the United States or in other countries.

Improved Service and Value Delivered to Guest. Another important benefit of having a labor management system is that it allows the deployment of the right labor both in quantity and in skill level at the right time to serve the guest. There are numerous occasions in which restaurants tend to control the total number of hours deployed in a restaurant; however, these hours may be deployed in such a fashion that they are available at a time that does not serve the guest well. For example, when neither labor nor productivity is a top priority, operators will be scheduled with long shifts—8 hours per day or 40 hours per week. Very few operators will be observed with short shifts focused on the times of guest arrival at peak meal periods (breakfast, lunch, and dinner). The labor management system (LMS) can significantly impact the deployment of appropriate amounts of labor at times that match the guest demands.

Development of a Productivity Culture. When a restaurant chain has an LMS, a culture in which there is a raised consciousness of labor productivity is created. Restaurant chains frequently make significant investments in technology, equipment, and better processes that should improve their operations. However, many times these improvements are not brought to fruition and the investments do not provide a return because of the lack of a productivity culture and the lack of a tool that can extract productivity improvements from the system in terms of improved labor costs. Labor management systems enable a productivity culture that gets food service facilities focused on the productivity issue.

Challenges

The engineer faces a number of challenges when developing a labor management system particular to the food service sector that are summarized in the following sections.

Customer Arrivals Are Concentrated in Short Periods of Time. Customer arrivals to food service operations are concentrated around meal periods, or conditioned by meal periods. These periods are typically described in the industry as peak hours or peak day parts—lunch, breakfast, or dinner. During peak hours or day parts, labor requirements can exceed off-peak requirements by as much as 400 percent, while the duration of those peaks of labor intensive periods is less than 30 minutes. Extreme examples of this situation are food service systems in entertainment complexes or stadiums where customers are available for periods as short as 15 to 30 minutes during game intermissions.

Use of Simple Manual Systems Inaccurate for Large Chains. Manual labor management systems are a relatively inexpensive solution to manage labor; however, due to the lack of computational capabilities, significant simplifications are made. These simplifications are favorable for some locations and unfavorable for others because of the variability introduced by different facilities, equipment, consumer demographics, regional menus, and employee proficiency. The larger the chain, the more significant these inaccuracies become, which renders a manual system impractical for a large chain with 100 or more locations.

Automated Systems Are Difficult to Integrate to Existing Technology. Implementation of an automated or computerized labor management system requires a significant effort to integrate information systems to commercial software or to develop software internally. This investment has to be offset by significant cost savings that can be achieved only with a significant number of locations.

Elements of Restaurant Labor Management Systems

There are a number of elements that have to be present for an LMS to be considered complete and, more important, to work effectively in this sector. Following is a list of basic components of a labor management system for food service operations:

- *Activity forecasting:* Activity forecasting is the module that would allow an LMS to forecast the activities that are critical to driving labor costs. There are a number of techniques that would be used. Most of them are naïve forecasting techniques, such as moving averages, exponential smoothing, or trend and seasonality. Activity forecasting systems should enable the manager to make changes to the forecast based on his or her knowledge of the business.
- *Workload calculation:* Workload calculation is the module of an LMS where work standards are applied to the activity forecast to calculate the total workload that will be required to serve the guest. This workload is calculated in half-hour or 15-minute increments in an automated system to yield a level of labor deployment that accurately matches requirements originated by customer arrivals.
- *Operator scheduling against workload requirements:* Once the required workload has been calculated for each half-hour or each 15-minute increment, specific workers have to be scheduled to fulfill those requirements. At this point, names are placed against given shifts that are in the system.
- *Performance reporting:* Performance reporting focuses on a wide variety of performance parameters; however, there are two basic items that must be tracked on a consistent basis. The first is performance against actual activity levels regarding the use of total labor-hours. This measurement will help control the total cost of labor in the food service facility. It is a control of labor-hours or of total dollars spent against labor. The other fundamental item is scheduling effectiveness. Scheduling effectiveness is a measure of how well operators scheduled are meeting the workload requirements. There are a number of approaches that can be used to measure scheduling effectiveness, but typically it is a percent of the hours that exactly match the workload for a given period of time.

- *Data management:* However simple the system is, data management consists of all the elements required to keep the system updated based on changes that occur in the operation. Examples of this are introduction of new products, new technology that improves productivity, promotions of certain products (that could require a focus on service), and settings such as minimum shift lengths allowed by law.

Minimum Requirements

There are minimum requirements that must be met to consider a labor management system an effective tool for a restaurant or restaurant chain.

Workload Calculation Against Actual Activity Levels. It is critical that an LMS be able to calculate workload against actual activity levels to create accountability. Many systems base the workload calculation or allowable hours calculations against forecast activity levels. This dramatically reduces the accountability of the food service operator to the food service facility performance, because the food service operator could constantly modify the forecast and therefore modify the workload allowances or the allowable hours. It is critical that a workload calculation be possible using actual past activity levels.

Performance Reporting of Labor Allowance Against Actual Activity Levels. It is also critical that performance reporting of labor allowances be done against actual activity levels. If it is done against other measures, such as performance reporting of labor allowance against forecast activity levels or against scheduled activity levels that may introduce some complex distortions, that will not allow appropriate performance tracking because the actual activity level may differ significantly from the forecast. Ultimately, actual performance is going to drive the success of the food service operation, and the operator should be able to understand the components of that performance in terms of the activities that actually took place.

Performance Reporting on Actual Scheduling Effectiveness. Scheduling effectiveness is a measure of how the actual operator schedule meets the workload requirements for serving guests. It is very important that performance reporting be conducted on scheduling effectiveness (even if it is calculated as a percent of times that actual workload is exactly matched to actual employees scheduled) so that there is a good understanding and a balance against total labor-hours. Total labor-hours can be reduced dramatically at the expense of the customer by increasing shift lengths and not covering the requirements of workload at peak activity times. Therefore, scheduling effectiveness is critical because it reveals whether the system is providing good coverage at the time when the customer needs it most.

Definitions and Conceptual Framework

To facilitate the understanding of some of the concepts in the development of an LMS, it is important to establish some definitions that are used in the industry and that will be helpful to refer to in subsequent sections.

Crew labor—all the labor in a restaurant that is paid a wage and performs cooking, cleaning, taking orders from customer, transacting cash or other forms of payment from customers, and serving orders to customers.

Managerial labor—consists of individuals that may be salaried, and who will perform most of the administrative and personnel duties, and the general management of the restaurant. It is common for a food service facility to be deployed with more than one manager (general manager and several assistants or other manager). Some companies also pay shift supervisors a salary as opposed to a wage.

Floor management—the managerial time that has to be dedicated in an LMS to the tasks that cannot be exactly measured, in frequency or duration. For instance, administrative tasks can be measured in most cases, but there are a number of tasks that a manager has to engage in that include directing employees on the floor and taking care of customers that need special care because they have a complaint or have inquiries to make. Floor management encompasses a number of items that are difficult to measure but that are a real component of a manager's function. These sorts of functions are usually measured using work sampling because it would be difficult to systematically develop standards for these approaches. This is typically quantified as a ratio between crew labor and management required—for example, as a 9 to 1 or 10 to 1 ratio between crew labor and floor management.

Managerial availability for crew labor—a concept that is widely used in the industry to improve overall productivity. It assumes that managers are going to be available when they do not have any floor management or administrative activities to perform but need to be in the food service facility for control purposes or emergency situations. It is presumed that under those conditions, they would be available to perform tasks that would typically be performed by the crew. For example, they may prepare food, help in cleaning, and take orders. There needs to be an understanding of how many hours on a daily or weekly basis would be available from the managerial team to perform crew tasks in order to reduce total crew requirements.

Fill availability—a concept similar to manager availability, but this applies to the crew. When a restaurant is deployed with a minimum crew, the amount of activities available for them to perform regarding customer service may not be sufficient to fully utilize them. Fill availability would be the percent of time a crew member would be available to perform fill tasks such as cleaning, food preparation, and preventive maintenance while simultaneously being responsible for customer service activities.

Scheduling effectiveness—the percent of time that a labor schedule exactly meets the workload requirements to serve the guest.

Scheduling efficiency—defined as a ratio between the workload required to serve the guest and the actual labor scheduled because of other constraints such as minimum shifts and operator availability. It is very difficult to find scheduling efficiencies over 90 percent.

Labor percent—the percent ratio between the cost of labor and the total sales of the food service facility. This concept is used widely in the industry to understand what labor costs are in comparative terms between different concepts.

Fixed labor—all those tasks that have to be performed constantly every day or week and performed a certain day or at a certain time. Examples of this are opening and closing activities.

Fixed-filler labor—this labor is fixed in regards to the total amount of time it takes to perform the task, but can be performed within a certain range of time. This is especially useful when developing the LMS because it allows the filling of relatively slow or idle times of the day with work to smooth out labor requirements, which, in turn, facilitates scheduling.

Variable filler labor—labor that is variable in regards to a driver of labor (for example, customer arrivals, sales, items sold) but that can be performed at different times of the day or within a range. A good example of this is food preparation that can be done several hours before customer arrivals. This type of activity could be used to fill an operator's time when underutilized performing customer service activities.

Customer service labor—all the labor that needs to be deployed and available shortly after customer arrivals or related very closely to customer arrivals: order taking, cashiering, making food, or cooking food to order.

Labor utilization—the amount of time or percent of time that labor is not idle. In delay studies, the status of an operator's activity may be described as walking, active, talking, or idle.

Point-of-sale (*POS*) *systems*—the computers or devices used to take orders from customers. The typical POS system used today consists of a touch screen PC-based system, which makes it an extremely sophisticated data collection and production scheduling device.

Development of Manual Restaurant Labor Management Systems

Manual labor management systems are an appropriate solution as a first step in implementing a productivity tool or when the implementation budget is limited. Given the limited computations that can be performed with this approach, it is necessary to make it as simple as possible. The drivers of labor have to therefore be limited to two, or at most three, variables. This approach will be inherently less accurate than an automated labor management system, so standards do not need to be set as precisely. Work sampling is generally used to develop customer service labor models, while stopwatch, professional, or expert estimates are used for all fixed activities. Variable filler food preparation labor is typically estimated for several stores and then averaged out on a per transaction, item, or sales basis. The recommended basic steps to develop a manual labor management system are described in the following sections.

1. Data Collection. This process is initiated by developing a form to perform a work sampling study. Observations should include the values of different potential drivers of labor (transactions, sales, items, guest counts, etc.) as well as the utilization status of all labor resources—managers included. Data on the customer service aspects are also essential to establishing a sound labor baseline. Food preparation schedules should also be collected at the store to attempt to establish the volumes of food needed for the operation. If estimated standards are available for each of the items produced, these need to be documented; otherwise, estimates need to be developed for each one. Fixed and fixed-filler tasks may be developed by expert or professional estimate.

2. Data Analysis. The data collected needs to be compiled to develop hourly labor tables for customer service. All observations are summarized to understand the correlation between speed of service and the utilization level that results in acceptable speed of service. Based on the speed of service objective of the operation and the function that correlates it to worker utilization, it is possible to establish the utilization that will deliver the required speed of service. This utilization level, deemed to be appropriate for good service, will be used to level and correct all other observations where utilization was either under or over the appropriate level to understand labor requirements. The analysis is completed by developing regressions between some of the driving variables and labor, which result in hourly, half-hourly, or quarter-hourly requirements.

3. Model Development. During the development phase, the engineer may implement a model with a level of complexity that may not be appropriate for field implementation but will allow the exploration of the minimum, simple variables that would be accurate enough to drive the system in the field. Due consideration will be given to fill availability, floor management, manager availability for crew labor, scheduling efficiency allowances, food preparation, fixed labor, and customer service labor. Typical drivers of labor include transaction counts, guest counts, item counts, sales, ticket average, product type counts (for example, burger type includes hamburger, cheeseburger, and bacon double hamburger), equipment type (dual versus single assembly line) or facility type (with or without drive through). Once a model is developed, in spreadsheet or database form, the engineer can establish the two or three critical variables that will drive labor allowances on a daily or weekly basis. The labor allowances are typically presented in a table format so that the restaurant operator can simply look up a value without having to perform any calculations.

4. Model Validation. The labor model will be validated in a number of ways. The first is to review the assumptions, data, and methodology with experienced and respected operators to ensure that it will reflect generally applied and accepted processes in the field. Discrepancies are a natural result of this step and can be addressed by adjusting the model or adapting the process (or policy) that causes the discrepancy. The second way to validate the system is to compare the LMS guidelines with actual labor costs in existing restaurants that are known to be well operated and appreciated by customers. Finally, it is important to assess the impact the LMS guidelines will have on financial performance. A restaurant chain may set performance goals for its service system that are simply impractical and/or uneconomical to implement. The resulting labor guidelines will have to be modified when more realistic performance expectations are set. A good example of this is speed of service. A full service restaurant chain may wish to serve its customers in less than 5 minutes, which will require significant additional labor when compared to serving customers in under 10 minutes. Decision makers may consider the cost of achieving the speed of service goal unacceptable and request modifying the guidelines to a more reasonable cost level.

5. Testing and Rollout (Implementation). The testing and rollout of an LMS to a restaurant chain must be done gradually, in an increasing number of sites. It is appropriate to start with two or three locations and then move to a whole market within close proximity of some or all of the two or three original locations; then an additional one or two markets can be added for a rollout simulation. To determine the number of locations, a good rule to follow is, less than 3 for initial testing, less than 20 for a second phase, less than 50 for a third phase, followed by systemwide implementation.

Development of Automated Restaurant Labor Management Systems

An automated LMS provides a number of significant advantages over a manual system. The first is that all computations are made by the system, thus enabling the use of more variables to drive the labor model more accurately. The second advantage is that the restaurant manager spends far less time dealing with the clerical aspects of labor management and can focus on operations, the customer, and training (as well as motivating) food service facility employees. The third advantage is that, due to its accuracy, it becomes a very fair performance measurement system across restaurants. A manual system, due to its simplicity, may oversimplify some of the variability inherent in a restaurant system, and some locations will be able to achieve labor guideline objectives easier than others.

The disadvantage of an automated LMS is that the software selected has to be integrated to an existing POS system to extract item, transaction, and sales data. Another alternative that is even more costly is to develop the LMS software internally, which is exactly what some large quick service restaurant chains have done very successfully. The recommended basic steps to develop an automated labor management system are as follows.

1. Data Collection. The data collection phase consists of identifying all the tasks that are performed in the restaurant and understanding all the variables (facility, equipment, processes, and city, state, and federal laws) that would affect work content. Once a list of tasks is identified, work content needs to be established for each of them. All tasks that entail customer interaction are typically measured using stopwatch studies, while other tasks can be measured using predetermined time standards, as well as stopwatch. Certain administrative tasks and floor management (and any other randomly occurring activities) must be quantified with work sampling techniques.

2. Data Analysis. In this step, the different tasks are classified and grouped to understand whether certain groups of products could use common standards to simplify future data maintenance. At this point it may be desirable to develop a computer simulation model of the restaurant system to establish the levels of operator utilization required to provide appropriate customer service.

3. Software Selection. The selection of software requires developing a request for proposal (RFP) to be submitted to at least three potential suppliers of labor management software. If you want to develop the software internally, it is a good idea to attend conferences and exhibitions to listen to presentations and to see demonstrations by suppliers. This ensures that the system developed internally will be competitive with existing commercial software. This RFP should be developed jointly with key functions of the restaurant chain: information systems, operations, finance, human resources, training, and marketing.

4. Software Integration. Typically, the software selected has to be integrated to existing POS and back office systems (BOS), unless it is part of that existing BOS. The scope of this effort can have a significant bearing on the timeline, feasibility, and profitability of pursuing an automated LMS.

5. Software Setup. At this stage, the integrated LMS software is set up with the appropriate standards related to variables that will drive labor. The engineer will also have to input utilization levels that will ensure good service to the customer.

6. System Validation. In addition to the validation steps outlined for manual labor management systems, it is important for the operator to verify that the system schedules labor not only in the right quantity but also at the times that are required to serve the customers and are practical for running a food service operation. In an automated system, labor schedules may reflect allocations of time to different tasks in increments as small as 15 minutes, while in a manual system those allocations may be expressed in terms of daily, or even weekly, requirements for *all* tasks. In a manual system, operators have the liberty of allocating labor as they please and the automated system's allocations should reflect the practices of the best operators in this regard.

7. Rollout. A gradual rollout approach should be followed as outlined previously for manual labor management systems: pilot test (up to 3 stores), market tests (up to 20 stores), rollout simulation (up to 50 locations), systemwide implementation.

SUMMARY AND FUTURE TRENDS

A systematic approach for food service facility planning has been outlined that integrates industrial engineering techniques to accepted practices in the food service sector. This integrates the practical experiences developed through successful designs and implementations. A process for developing labor management systems has also been outlined to address the management of the largest controllable cost in food service facilities. These two processes work together to optimize operations of a food service chain. Systematic facilities planning ensures that all productivity improvement opportunities are addressed, while implementation of a labor management system ensures that the resulting cost savings are managed appropriately.

Companies in the food service sector are constantly seeking opportunities to reduce and control labor costs and reduce the size of facilities out of which business is conducted while greatly increasing guest convenience and value provided in terms of food quality, price, and service. This represents a significant opportunity for industrial engineers to focus on eliminating or improving all steps from a process that add little value to the guest. Industrial engineers have been very successful at eliminating non-value-added steps in the manufacturing and service sectors, and are likely to succeed in food service as well.

FURTHER READING

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BIOGRAPHIES

Tom Wyczawski, owner of Strategic Restaurant Engineering, Inc., has been managing engineers and engineering projects for over 15 years both as a consultant and as an engineering manager for Fortune 500 companies. Working for General Motors, McDonnell Douglas, and PepsiCo, he has implemented large productivity improvements through facilities planning, process improvement, labor control systems, production and inventory control systems, and world-class manufacturing. He has completed food service facility plans or labor management systems for ARCO, Boston Market, California Pizza Kitchen, Taco Bell, El Pollo Loco, Allied Domecq Retailing, Universal Studios, Panda Express, Epcot, and Jack in the Box.

Mark Godward, owner of Strategic Restaurant Engineering, Inc., has been leveraging his strong quantitative and technological background for over 15 years to achieve consistently superior results as a project/engineering manager and consultant. Working for Ford Motor Company, Tompkins Assoc., General Tire & Rubber Company, and PepsiCo, he has used computer simulation, linear programming, computer-aided facilities planning, statistical analysis, labor control systems, production and inventory control systems, and advanced manufacturing techniques to successfully implement significant operational improvements. Mark has completed food service facility plans or labor management systems for Pizza Hut, Boston Market, Starbucks Coffee, Einstein Bros. Bagels, Noah's Bagels, Jamba Juice, Taco Bell, Hot 'n' Now, Rubio's Baja Grill, World Wrapps, Applebee's, Baskin-Robbins, and Denny's. In 1994, he received the President's Award at Taco Bell and the Operations Research Application Award from the Institute of Industrial Engineers.

CHAPTER 15.3

HEALTH SERVICE

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This chapter will discuss the application of some of the industrial engineering (IE) techniques commonly used in improving quality and productivity in health care delivery systems. The techniques such as methods improvement and work simplification, staffing, scheduling, queuing and simulation modeling, optimization, and quality analysis and improvement will be discussed using various hospital departments as examples. The emphasis will not be on the techniques, but rather on the applications of them in health care. A table is provided that summarizes the various references by the type of technique and the area of application in the health services. A brief history of health care delivery systems and key issues and trends is also provided for readers who are unfamiliar with the health care industry. The chapter ends with a discussion of the future of IE in health services.

INTRODUCTION TO HEALTH CARE DELIVERY SYSTEMS

During the past 200 years, hospitals have acted as a hub for the health care delivery system. Most hospitals were founded as charitable organizations to serve the needs of communities. Although there were a number of facilities on record taking care of patients in the late 1600s, the first incorporated hospital in America was Pennsylvania Hospital, located in Philadelphia, in the year 1751. Benjamin Franklin aided in the design of the hospital and served as its first president from 1755 to 1757. The early hospitals were founded to house people during epidemics. In early 1873, there were only 178 hospitals and fewer than 35,000 beds in the United States. The growth of medical technology changed the role of hospitals from public health functions to patient treatment facilities. The introduction of anesthesia in the 1840s allowed more serious operations to be performed. The understanding of infection, the transmission of infection from doctor to patients, and from patients to other patients, in the period 1850 to 1900, further changed the role of hospitals. Mortality rates from infection dropped significantly during this period. The discovery of the x-ray in 1895 further introduced technology into the hospitals. The introduction of technology also changed the role of hospitals from depositories for poor people to community resources, where community physicians could share high-cost equipment. The number of hospitals grew rapidly, and by 1909 there were 4300 hospitals with over 420,000 beds, a major increase from the 1870s level [1].

Gradual growth occurred in the hospital industry from 1910 to 1965. A major construction boom occurred with the passage of the Hill-Burton Law, enacted in 1948. The program was designed to provide matching funds to towns without a community hospital. This federal legislation was responsible for most of the small (fewer than 100-bed) hospitals that developed during the 1950s and 1960s. The next major growth period for hospitals occurred with the passage of Medicare legislation in 1965. The legislation provided care for the nation's elderly (over 65 years). A companion legislation introduced the Medicaid program, meant to cover the poor. By 1979, the total number of hospitals reached 7099, of which 377 were federal and 6722 nonfederal [2].

Hospital Ownership

Government-owned hospitals account for 50 percent of the total number of hospitals in the country and include federal, state, county, and city hospitals. Federal hospitals include Army, Navy, Air Force, and Veterans Administration hospitals.

The nongovernment hospitals' ownership is divided among church-related groups, community, not-for-profit hospitals, and investor-owned or for-profit hospitals. Not-for-profit community hospitals constitute the bulk of the hospitals in the country. These hospitals are owned and controlled by the community in which they are located via a voluntary board of community leaders. For-profit hospitals originally were owned by physicians and were small, usually fewer than 100 beds. During the 1960s and 1970s, several investor-owned chains were formed. Notable among them are the Hospital Corporation of America (HCA) and Humana, both of which are traded on the stock exchange. In the 1990s, two for-profit chains owned a large number of hospitals, namely Columbia with over 300 hospitals and Tenet with over 100 hospitals nationwide.

Hospital Regulations

Numerous state, federal, county, and city agencies, numbering over several hundred, regulate hospital operations. Hospitals are generally licensed by an agency of the state, usually the health department. These regulations primarily cover physical facilities, management, medical staff, safety, drugs and pharmaceuticals, and personnel, as well as medical records. Most states also regulate the building and expansion of health care facilities through a "certificate-of-need" program, commonly operated by the state department of public health. The objective of this regulatory effort is to control the expansion of facilities and services in the public interest.

During the 1960s and 1970s, many health care regulations were passed. The focus of most of these legislations was the control of hospital growth through the formation of health care planning agencies and professional standards review organizations (PSROs). The PSRO review determines whether services are medically necessary.

Planning

After the enactment of the Hill-Burton program in 1948, many voluntary planning agencies developed at the state level. New York State was the first in 1964 to enact a mandatory health planning law. This law required prior state approval before any hospital construction or expansion could take place. The criterion for expansion was demonstrated need, and a new facility had to be consistent with the state plan for the delivery of health care. After the Medicare program was enacted, a number of states developed certificate-of-need programs. Any hospital planning to expand or build a new facility required approval from the state planning agency [2]. In 1974, the U.S. Congress enacted Public Law 93-641, labeled the National

Health Planning and Resources Development Act. This law created organizations at the national, state, and local levels to conduct health services planning. The law required hospitals that participate in Medicare or Medicaid to obtain planning approval for capital expenditures over $100,000. A huge bureaucracy developed at local, state, and national levels to implement this law. Most experts agree that this legislation was a dismal failure, as evidenced by national hospital occupancy levels of 60 percent [3]. Most of the states have revised or drastically reduced the scope of this law. Many states have changed the review limit to $1 million. In other states, only the construction of new hospitals or new beds is reviewed.

Hospital Revenues

In most nongovernment hospitals, the principal sources of revenue are patient services. The past 30 years have seen a dramatic change in health care revenue sources with increasing numbers of people covered by insurance. The largest of these programs is the Medicare program that covers people over the age of 65 and people eligible for social security benefits. A typical hospital receives approximately 35 percent of its revenue from Medicare patients. The federal government, through an agency called the Health Care Financing Administration (HCFA), manages this program. From the enactment of the Medicare legislation in 1967 until 1983, Medicare paid hospitals on the basis of cost. To control the rising cost, a variety of methods was used, including cost increase ceilings, but without much success. Finally, in 1983, a revolutionary new means of payment was introduced, known in the industry as the diagnostic related group (DRG) payment system. Under this system, hospital cases are divided into 487 different classes based on diagnosis, age, complications, and the like. For each of these diagnostic groups, a predetermined payment level is specified. If the hospital can deliver care at a cost lower than the payment, the hospital is entitled to keep the difference. On the other hand, if the hospital costs are higher, the hospital incurs a loss. Many of the commercial insurance companies such as Blue Cross and Blue Shield, as well as state Medicaid programs, have adopted this method of payment for the hospitals.

Key Issues and Trends

Between 1965 and 1980, the hospital industry fell under the umbrella of multiple regulatory approaches. Most of these regulatory approaches failed to control the increases in health care expenditures [3]. More recently, the industry has moved toward a competitive model. During the past decade, a few key trends have emerged as summarized in the following paragraphs.

Economics. Health care premium increases continued at a pace exceeding over 10 percent per year during the 1970s and 1980s. Faced with managed care and a competitive marketplace, the health care premiums decreased nationally during the period of 1995 through 1998. The rate of premium increase reached a high of between 15 and 30 percent in 1983 and a low of between 5 and 10 percent during 1996. The length of stay has continually dropped in the hospitals from an average of more than 10 days in the 1970s to less than 5 days in 1997. Hospital admission rates have also dropped during this period. Many of the procedures done on an inpatient basis are now being performed on an ambulatory care basis. In contrast to the decline in the inpatient setting, outpatient and ambulatory care continue to grow at a pace of over 10 percent a year. Most analysts believe that inpatient admissions and length of stay will continue to decline and the ambulatory health care will continue to grow over the next decade.

Financing. The private health insurance market has been shifting from indemnity insurance to managed health care. Health maintenance organizations (HMOs) have grown at a rapid pace during the past 10 years and now account for 70 million people in some 500 different plans. Recently, employers have been changing their health care insurance strategy from providing benefits to providing fixed payments toward health care benefits. More coinsurance and deductibles are being introduced.

At the federal level, Medicare has reduced payments to the providers by recalibrating DRG payments downward, raising deductibles for the elderly, reducing payments for medical education, and limiting price increases to well below the cost increases in the industry. Current trends point to continued federal retrenchment with projected reductions in capital cost reimbursements and medical education costs [4].

The Medically Indigent. The number of people who have neither medical insurance nor coverage by federal and/or state programs, continues to rise. Latest estimates indicate that some 40 million people are medically indigent. In the past, hospitals have cross-subsidized indigent care. But as the industry has moved to prospective-payment and fixed-payment systems, hospitals are unable to transfer the costs of indigent care to other payers. As a result, hospital net patient margin has been decreasing.

Medical Staff. During the past 30 years, there has been a dramatic increase in the number of physicians. Since 1950, the number of physicians has grown 150 percent. The number of medical school graduates has increased from approximately 7000 in 1960 to 20,000 in 1996. Physicians in active practice now number over 600,000.

The number of registered nurses (RNs) has grown from 750,000 in 1970 to over 1.2 million now. Even with this growth, hospitals are currently experiencing tremendous shortages in RN staffing, especially in such areas as intensive care units, special care units, and emergency rooms. The nursing shortage can be attributed to the high percentage of nurses dropping out of the nursing field. In addition, nurses have many other opportunities within health care, aside from the inpatient setting, including such areas as ambulatory care, utilization review, quality assurance, home health agencies, and ambulatory surgery. Nurses have found that these positions do not require night-shift rotation or weekend coverage. With the baby boom age group approaching retirement, the nursing shortage is projected to continue in critical areas.

Medical Liability. The health care industry has gone through several medical malpractice crises in the last decade. Nationwide, the cost of medical malpractice has increased to over $5 billion per year. In some years, malpractice insurance costs jumped 30 to 40 percent. The most common claims deal with surgical cases, followed by claims for improper treatment or failure to diagnose. Certain specialties have been hit harder than others; these include obstetrics and gynecology, orthopedics, and neurosurgery.

Industry Structure. The health care industry has been experiencing two major structural changes in response to the environmental changes facing the industry: (1) diversification and (2) industry consolidation. Hospital corporations are increasingly defining their mission as *health care* as opposed to *inpatient hospital care.*

Increasingly, hospitals are developing ambulatory care programs that include ambulatory care clinics and ambulatory surgical centers. Other areas of growth include home health care and durable medical equipment.

Two major reasons for the growth of ambulatory care facilities are (1) the growth of HMOs and (2) the need for hospitals to fill beds. Hospitals have developed freestanding ambulatory care centers as a means of penetrating new markets and gaining referral to the inpatient facilities. The growth of HMOs requires that they are geographically accessible to the population, and freestanding primary care centers are a means of providing accessible primary care services.

The other major trend is consolidation within the industry. Increasingly, hospitals are joining together to form stronger economic entities. In Detroit, Cottage Hospital, Riverside Hospital, Bi-County Hospital, Kingswood Hospital, Wyandotte Hospital, Henry Ford Hospital, and Health Alliance Plan have joined to form the Henry Ford Health System. Similar consolidations are taking place all across the country. Industry consolidation and diversification will continue and will gain momentum in the coming years. In most large cities, the top four health systems control over 70 percent of the hospital admissions.

IE IN HEALTH SERVICES

The use of IE techniques in health services started with the use of *methods improvement,* which was part of the teachings of Frederick W. Taylor, commonly known as *The Principles of Scientific Management* [5]. Frank Gilbreth is considered to be the first person to use methods improvement in a hospital situation by applying his motion study techniques to surgical procedures [6, 7]. In the 1940s, Lillian Gilbreth urged hospitals to benefit by the use of IE tools and techniques [8, 9]. In 1951–1952, Lillian Gilbreth, Ruth Kuehn, and Harold Smalley collaborated in an organized effort to apply methods improvement to the entire hospital organization. The result was a two-week workshop conducted at the University of Connecticut in July 1952 [10].

Because of the interest shown by a large number of hospital administrators in the techniques of methods improvement, the American Hospital Association (AHA) created a committee on methods improvement in 1952. This committee prepared several papers on methods improvement activities and published them in its interim report in 1954. By the late 1950s, hospitals, the AHA, and various universities started promoting methods improvement by offering in-service programs at hospitals, workshops around the country, and various courses in education curricula. Industrial engineering courses were offered in hospital administration curricula. Gradually, other IE techniques were studied and applied to various hospital problems. In 1961, the Hospital Management Systems Society (HMSS) was founded in Atlanta, with Harold Smalley serving as its first executive director. In 1964, the national offices of HMSS moved to the AHA building in Chicago. In 1987, recognizing the important role played by information systems in health care, the society was renamed the Healthcare Information and Management Systems Society. The Institute of Industrial Engineers also recognized the expanding role of IE techniques and formed a hospital division in 1964. This section changed its name to the Health Services Division in 1977, reflecting the broader scope of the field. In 1988, the Society for Health Systems was formed to replace the Health Services Division.

During the past 25 years, the use of IE techniques in health care systems continued to grow. Many industrial engineers obtained employment in hospitals and health systems, and others worked as consultants in health care. The use of the term *management engineering* to represent IE as practiced in the health care field became common. A detailed history of the development of hospitals and hospital management engineering is covered by Harold E. Smalley in his book, entitled *Hospital Management Engineering* [10].

Some of the IE techniques that have been used in health care systems include:

- Methods improvement and work simplification
- Performance and productivity measurement
- Staffing and scheduling
- Work sampling
- Queuing and simulation modeling
- Optimization
- Personnel management
  - Job analysis
  - Wage incentives

  - Merit rating
  - Suggestion plans
- Variability analysis and control
- Demand forecasting
- Production and inventory control
- Facilities planning
  - Layout
  - Handling systems
  - Warehousing
- Labor and budget control
- Quality analysis, control, and improvement
  - TQM/CQI
  - Reengineering
- Economic analysis
- Project management
- Capacity analysis
- Product management
- Information systems and request for proposal (RFP) process

Applications of some of these techniques will be discussed using various hospital departments as examples. A brief introduction will be given for each of the hospital departments used in the examples. The emphasis will not be on techniques but, rather, on the application of techniques in health care. Details about IE techniques are given in other chapters of this handbook. A beneficial description of various hospital departments is available in the book *Hospital Department Profiles* [11].

METHODS IMPROVEMENT AND WORK SIMPLIFICATION

These are the industrial engineering tools and techniques that are used to improve the work methods applied by health care employees in the delivery of health care. The work methods under consideration are those utilized in direct health care as well as in support activities. Management engineers use a number of different charts to document a process or work method. These charts facilitate the critical evaluation of the various steps of the process and lead to the identification and correction of flaws in the process. Some of these charts include the following:

- Flowchart
- Flow process chart
- Flow diagram
- Paperwork simplification chart

Flowcharts are very commonly used to track an existing process for evaluation or to chart a new process to be implemented. They show each step of the process and appear very similar to the flowcharts that are associated with computer programs; they show the decision points, as well as the various possible courses in action.

Application in Radiology Departments

Figure 15.3.1 shows the flowchart for merging a temporary folder with the master folder for a patient in the radiology department on a computerized film tracking system. A radiology department in a hospital or outpatient facility is responsible for taking x-rays, interpreting the films, and conveying the results to the physician who ordered the x-rays. It is also responsible for maintaining and storing the folders containing radiological films and the radiologist's reports for each patient. When the radiology folder is needed for a patient appointment, the radiology department locates the folder and sends it to the physician's office. Most radiology departments use some type of tracking system to track the location of these folders. In certain situations when the master radiology film folder is not available, a temporary folder may be created, which is later merged with the master folder when it becomes available. The flowchart clearly shows the various steps in the merge process done on a computerized radiology information system. A critical examination of each step can be used to make improvements in this process. The flowchart may also be used to train employees in the radiology department in performing the merge on the information system.

Flow process charts show operations, inspections, transportation, storage, and delays associated with a process. A flow diagram is a layout of the department showing the locations where various activities take place. Paperwork simplification charts are beneficial for charting the uses, functions, and information flow taking place. They focus on the efficient use of paperwork to provide the needed control and communication. For example, they can be used to chart the processing done on a service memo and its copies following an outpatient visit.

STAFFING

Staffing dictates the number of employees of a given skill level needed in the department to meet a given demand for services. Scheduling determines the days, shifts, and hours each individual is assigned to work.

The determination of the staffing level requires the listing of all the different tasks done by a certain skill level in the department and the measurement of the work content associated with each task. The total number of hours of work to be performed by skill level is determined for a given demand level, which then forms the basis for staffing level after demand variability, desired coverage, scheduling constraints, and the like are factored in.

The measurement of work content associated with each task can be done by using common work measurement techniques such as stopwatch time study, predetermined motion time systems, work sampling, or a combination of these techniques. These measures of work content are commonly called *staffing standards* and represent the standard hours of work associated with a task. These measured staffing standards can be used to determine the staffing needs for anticipated demand level or to determine staff utilization for an actual demand level. An inherent drawback to the use of measured staffing standards is that the process is very complex and time-consuming. Moreover, any time the method changes, the standards must also be changed.

An alternative to using measured staffing standards is to employ one of the various standard staffing methodologies available in the health care industry. These methodologies describe the typical tasks that are performed in a particular hospital department and assign a standard time to each of these tasks. Some of these systems include a large number of different hospital departments. One such system is called the *resource monitoring system* (RMS) and was developed by the Hospital Association of New York State [12]. Under these methodologies, the departmental tasks are classified as *constant* or *variable.* Constant tasks are those not directly related to departmental output (i.e., they are independent of the level of demand for services). Variable tasks are directly related to the output of the department. For example,

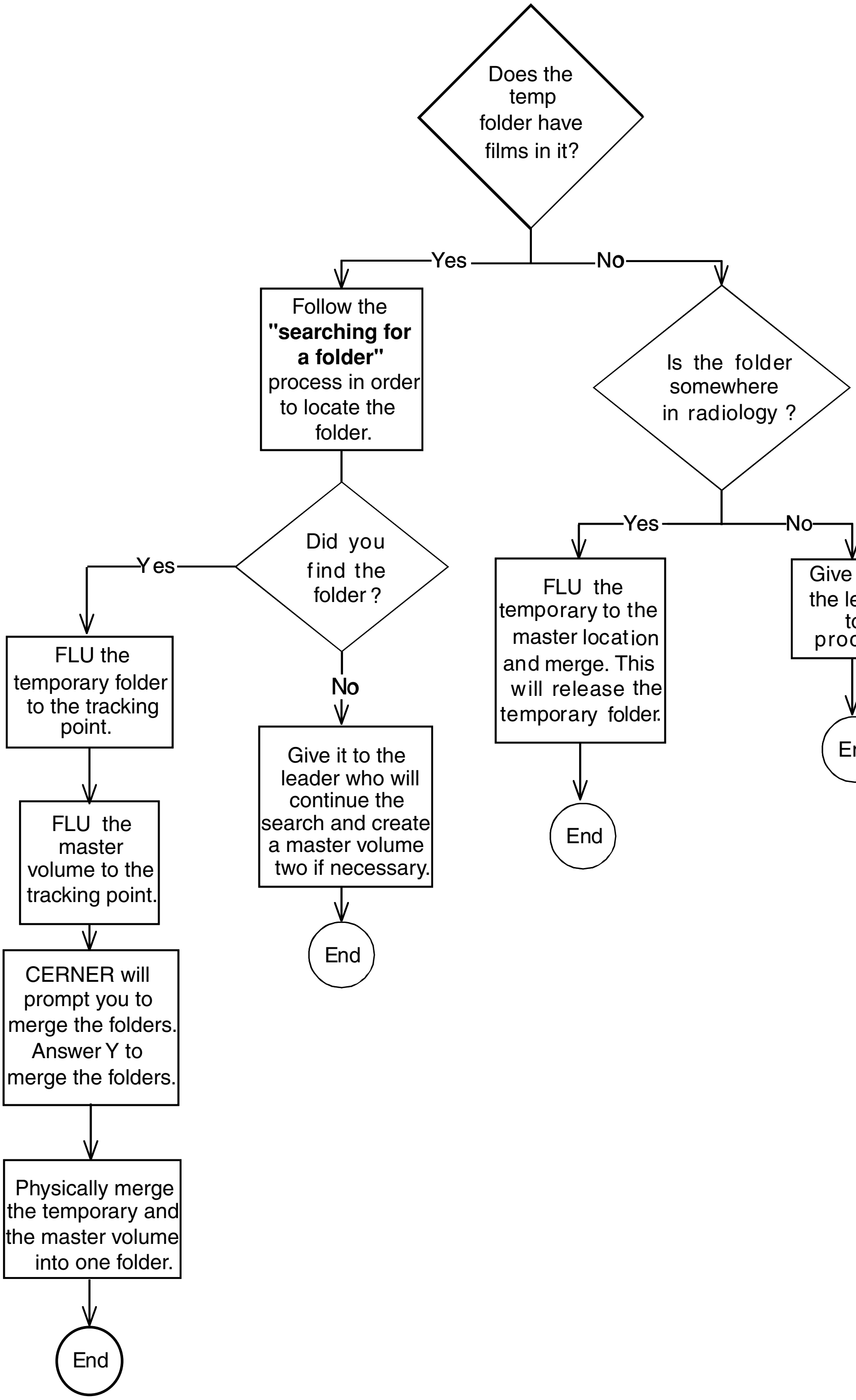
Does the temp folder have films in it?
Yes
No
Follow the **"searching for a folder"** process in order to locate the folder.
Is the folder somewhere in radiology ?
Did you find the folder ?
Yes
No
Yes
No
FLU the temporary folder to the tracking point.
FLU the master volume to the tracking point.
CERNER will prompt you to merge the folders. Answer Y to merge the folders.
Physically merge the temporary and the master volume into one folder.
End
Give it to the leader who will continue the search and create a master volume two if necessary.
End
FLU the temporary to the master location and merge. This will release the temporary folder.
End
Give it to the leader to process.
End

FIGURE 15.3.1 Flowchart for merging a temporary folder with a master folder on a computerized film tracking system.

in the electrocardiograph (EKG) department, a constant task element may be the daily cleaning of the machine, and a variable element is the actual performance of a test.

The total department workload in standard hours can be determined by:

$$T = C + V_1T_1 + V_2T_2 + \cdots + V_nT_n$$

where T = total department workload in standard hours for a day
C = total time consumed per day by all the constant tasks in standard hours
V_i = number of times variable task i is done during the day $(i = 1, 2, \ldots, n)$
T_i = standard hours associated with the performance of variable task i once $(i = 1, 2, \ldots, n)$
n = total number of variable tasks

$$\text{Department efficiency} = \frac{T}{\text{Actual hours spent}}$$

$$\text{Theoretical full-time equivalent (FTE) needed} = \frac{T}{\text{Hours available per FTE per day}}$$

The actual required FTE will depend on demand variability, coverage issues, scheduling constraints, skill level requirements, and similar factors. One approach is to determine the maximum efficiency level E that could be expected because of these factors. Actual FTE needed would then be given by:

$$\text{Actual FTE needed} = \frac{T}{(\text{Hours available per FTE per day}) \times E}$$

The seven basic steps needed to apply these methodologies are as follows:

1. Document the workload mix for the department for a selected period of from two to four weeks.
2. Check the methods and procedures used in the department against those given in the methodology.
3. Verify the standard times for various tasks as given in the methodology.
4. Obtain standard times for tasks not available in the methodology using work measurement methods such as stopwatch time study.
5. Compute the total workload in standard hours for the study period.
6. Divide the total workload by the actual hours worked to determine efficiency.
7. Compute the efficiency each week to monitor deviations and to determine whether staffing adjustments are needed.

A Case Study in the Pharmacy Department

Foley and Kubel [13] applied the workload indicators developed and published by the Canadian Society of Hospital Pharmacists. The pharmacy department in a hospital serves inpatients and outpatients by filling the prescriptions written by the physicians. The major functions performed are the dispensing of medicine, maintenance of medication administration records, maintenance of medication inventory at nursing units and other hospital departments, preparation and provision of intravenous solutions to nursing units, preparation and delivery of unit doses to nursing units, purchase of drugs, and warehousing of drugs. The management engineers are involved in the analysis of overall work flow, staffing, purchasing and inventory analysis, implementation of unit dose systems, charging procedures, paperwork analysis, and evaluation of pharmacy information systems. Table 15.3.1 shows the computa-

TABLE 15.3.1 Computation of Total Workload per Day Associated with TPN Units at a Hospital Pharmacy*,†,‡

Ref. no.	Element	Workload indicator	Skill level	Time/standard	Volume/day	Total
6.2.3	Calculate TPN orders	TPN orders	RPh	1.68	2	3.36
6.2.5	Prepare TPN solution level	TPN units	RPh	1.21	3	3.63
6.2.6	Prepare clean environment and personnel	Occurrences	RPh	5.34	2	10.68
6.2.7	Obtain and assemble pharmacy items	TPN units	RPh	1.17	3	3.51
6.2.11	Prepare TPN solutions	TPN units	RPh	16.2	3	48.6
6.2.13	Inspect TPN solutions	TPN units	RPh	0.65	3	1.95
6.2.14	Affix labels	TPN units	RPh	0.54	3	1.62
6.2.15	Verify TPN solutions	TPN units	RPh	0.67	3	2.01
6.2.17	Record TPN solutions	TPN units	RPh	0.64	3	1.28
6.2.18	Cleanup	Occurrences	RPh	3.64	3	7.28
6.2.19	Transfer TPN solutions to delivery area	TPN units	RPh	0.16	3	0.48
6.2.20	Deliver TPN solutions	Ward chart	Tech	3.04	4	12.16
6.4.4	Monitor laboratory orders	Reviews	RPh	1.8	2	3.6

Source: *Reprinted with permission from Foley, Michael F., and Jeffery E. Kubel, "Comprehensive Pharmacy Department Workload Analysis System—A Case Study,"* Proceedings of the 1998 Annual Healthcare Systems Conference, *vol. 1, 1988.*

* TPN, total parenteral nutrition; RPh, registered pharmacist; Tech, pharmacy technician.

† Total minutes = 100.16; total TPN units = 3.

‡ Total TPN minutes = 100.16; total TPN units (3) = 33.4 min per charged TPN solution = 0.57 hours charged per dose.

tion of total workload associated with the preparation and delivery of the total parenteral nutrition (TPN) units per day in a hospital pharmacy.

SCHEDULING

Scheduling in health care systems can take two forms: (1) the scheduling of personnel in a department based on the varying demand for services during the various hours of the day while providing equitable scheduling for each individual and (2) the scheduling of work, which may be a possibility in some departments, to balance the workload among days of the week and hours of the day, matching the workload with staffing levels.

In personnel scheduling, the staff is assigned to a specific pattern of workdays and off days. There are basically two types of scheduling patterns: (1) cyclical and (2) noncyclical. In cyclical patterns, each individual's work pattern is repeated after a given number of weeks. Usually, a number of workers share the same cycle. The advantages of the cyclical schedule are the staff members' knowledge of their predictable long-term schedules, and the need for changes only when the workload—that is, the staffing requirements—changes significantly. The disadvantage is the inflexibility of the cyclical schedule to accommodate both demand fluctuations and individual needs of workers.

In noncyclical patterns, a new schedule is generated for each scheduling period (usually two to four weeks) and is based on expected demand and available staff. This approach provides flexibility but is time-consuming and allows little advance planning for workers. Another pattern that can be used allows for four 10-hour days per week or 12-hour shifts or flex scheduling. Personnel schedules are developed either by using a heuristic, trial-and-error approach or by using some optimization technique. There are several computerized systems available using both types of approaches.

Nurse Scheduling

The nursing department is responsible for providing direct patient care to all the inpatients and outpatients in conjunction with the physicians. The nursing director is responsible for nursing in medical and surgical inpatient units, specialty units, and in some cases, in the emergency room, operating room, and ambulatory care. The role of management engineers in a nursing department may involve methods analysis on a nursing unit, quality of care, staffing analysis, scheduling, and computerized nursing information system development. Management engineers are also involved in the development of patient classification systems based on patient acuity. The patient classification system determines the staffing needs relative to the patient census on a nursing unit and the acuity level of these patients.

Warner [14] developed a computer-aided system for nurse scheduling that maximizes an expression representing the quality of schedule subject to a constraint that minimum coverage be met. This system will be discussed further under the section entitled "Optimization." Sitompul and Randhawa [15] provide a detailed review and bibliography of the various nurse scheduling models that have been developed. They suggest the development of a decision support system that allows the use of a structured model as well as subjective assessments in an interactive mode. This system could provide optimal schedules while allowing the flexibility and speed of heuristic and representational procedures of artificial intelligence.

Work Scheduling

Some of the areas where work scheduling is possible are elective admission scheduling, case scheduling in operating rooms, appointment scheduling in clinics, and scheduling for radiological procedures and other testing. The most common approach to work scheduling is *peak load analysis,* where the workload and the associated staffing requirements are plotted by the day of the week and hour of the day to identify the peaks and the valleys. Attempts are made to smooth out the peaks and valleys in demand. Another approach is to study the statistical distribution of demand by hour of the day and staff to meet the demand a certain percentage of time (e.g., 90 percent). After the staff schedule is determined, the work schedule basically follows it. Some key issues associated with work scheduling are no-show rates, overbooking, and block scheduling, which must be analyzed to develop appropriate policies. The computerized systems basically allow the computerization of manual appointment books with the capacity to check the availability of resources needed for the task to be performed. These systems can search for available appointments meeting the time restrictions of the patient.

Case Scheduling in the Operating Room

The operating room, or surgical department as it is sometimes called, consists of the preop room, operating rooms, and recovery room. The surgery may be performed on inpatients who are admitted at least one day prior to surgery, outpatients who come in for minor procedures to be done under local anesthetic, or ambulatory surgery patients who have certain procedures done under general anesthesia and are discharged the same day. The role of the management engineer in a surgical department may involve methods analysis to reduce delays and improve patient flow, quality, and productivity; staffing analysis; case-scheduling analysis; layout development; materials management; and information system selection or development.

Kachhal and Koch [16] discuss the functional requirements associated with scheduling a case in the operating room and evaluate the capabilities of the software systems available on the market for meeting these requirements. To carry out the case-scheduling function effectively, software should have the capability to:

- Schedule cases a predetermined number of weeks in advance
- Schedule cases for a duration based on the history of the surgeon-specific and procedure-specific times
- Block schedule by surgical specialty
- Restrict scheduling of certain cases in certain rooms
- Check the availability of the specific surgeon, anesthesiologist, nurse, and equipment prior to scheduling a case
- Check credential information prior to scheduling a case

There are a number of software programs available which are able to meet most of these requirements. Management engineers are often involved in the development of function requirements in conjunction with the department personnel to be used in a request for proposals to potential vendors.

Another issue in case scheduling is the determination of the optimal sequence in which a given group of cases assigned to a surgical suite must be performed and the assignment of the estimated starting times to these cases. Weiss [17] discusses a procedure for accomplishing this using an analytical, as well as a simulation, model while balancing the operating room idle-time costs and the surgeon's waiting-time costs.

QUEUING AND SIMULATION MODELING

There are a number of situations in health care systems where the customers must wait for service from one or more servers. Some examples of these situations are

- Outpatients waiting for service from a receptionist, nurse, or physician in a clinic
- An emergency room patient awaiting service from a receptionist, nurse, or physician
- A surgeon waiting for the operating room to become available in order to perform the next surgical procedure
- Patients awaiting ancillary services such as blood drawing in the laboratory or x-rays in radiology
- Phone callers waiting to be answered by the receptionists at an appointment scheduling center
- Patients waiting to be moved from one location to another by the patient transporter

The objective is to design the systems with the appropriate number of servers to obtain a proper balance between the average customer waiting time and the server idle time. The interarrival time for customers and the service times are random variables. To analyze the preceding problems, one needs to first determine the probability distribution of the interarrival times between two consecutive arrivals in addition to the service times. The service discipline and the effect of queue length on arrival rates, if any, also need to be known. In some simple situations, an analytical queuing model can be applied to analyze the situations and obtain preliminary results. In more complex situations, simulation modeling is employed to design the system. Simulation models allow you to investigate various assumptions for arrival time and service time distributions, or to compare various designs easily.

Queuing and Simulation Models in the Emergency Room

An emergency room is the central facility in a hospital for the treatment of medical cases that require immediate attention. These cases may include injuries or life-threatening illness such as heart attacks and drug overdoses. Emergency rooms also treat nonemergency cases after regular clinic hours, such as return visits for change of dressing or suture removal. In an emergency room, a triage nurse determines whether the patient requires immediate medical attention and sets up the sequence in which the attending physicians treat the patients. The treatments are not first-come-first-served generally, but rather follow the priority groups. The emergency room also requires additional diagnostic services such as x-ray and laboratory.

One critical issue in the emergency room is the proper staffing of nurses and emergency physicians based on the probabilistic demands that may vary by hour of the day and day of the week. Hale [18] used a multiple-server queuing model with patient arrivals following a Poisson process and exponential distribution for treatment times. From the data collected over a period of time, he was able to verify the validity of assumptions made in the model and to determine the average waiting time and average number of patients waiting for service. Ortiz and Etter [19] also applied a similar queuing model to the emergency room but determined that the assumption of exponential treatment times was not valid for certain types of cases. They found simulation modeling to be a better approach even for simple, less complex systems because of its flexibility and capacity to investigate various alternatives. They used a general-purpose simulation system (GPSS) to simulate the emergency room. Dawson et al. [20] used simulation models to determine optimal staffing levels in the emergency room.

Simulation models have been extensively used in order to study a variety of departments and activities in health care systems. Dumas and Hauser [21] developed a simulation model to study various hospital admission policies. Kachhal, Klutke, and Daniels [22] used GPSS to simulate outpatient internal medicine clinics in order to investigate various clinic consolidation options. They used another model to determine optimal staffing for audiologists administering hearing tests ordered by ear-nose-and-throat (ENT) physicians. Levy, Watford, and Owen [23] developed a simulation model using simulation analysis (SIMAN) to assist in the design of a new outpatient service center. Cirillo and Wise [24] used simulation models to test the impact of changes in a radiology department. Schroyer [25] used a simulation model to plan an ambulatory surgery facility.

OPTIMIZATION

There are a number of situations in health care systems that require the best possible (optimal) use of resources to meet certain objectives. Many of these problems can be formulated as mathematical models that can then be solved as optimization problems using linear programming, integer programming, branch-and-bound methods, or various nonlinear optimization methods. Some examples of the applications of optimization techniques in health care systems are given in the following paragraphs.

Warner [14] formulates the problem of determining the optimal nurse schedule as a two-phase, multiple-choice programming problem and solves it using a modified version of Balintfy's algorithm. In his formulation, the objective is the determination of the schedule that maximizes an expression representing the quality of the schedules, quantifying the degree to which the nurses like the schedules they would work. The solution is determined subject to the constraints that the minimum coverage requirement for each shift and for each skill level be met. In those cases where the minimum coverage cannot be met, the seriousness of coverage violation is minimized. This optimization model is the basis of the ANSOS nurse scheduling software used in the health care industry. Warner, Keller, and Martel [26] discuss automated nurse scheduling software.

Trivedi [27] studies the problem of the reallocation of nursing resources at the beginning of each shift. This reallocation is needed because of the daily variation in the demand for nursing time on a unit, resulting from variation in census as well as patient mix. Nursing staff size and mix may also vary because of absenteeism and the 24-hour-a-day, 7-day-a-week coverage requirement. Trivedi develops a *severity index,* which is a measure of the need for an additional staff member by skill level, and obtains regression equations for each of the nursing units relating severity index to staff size, census, and patient classification. The mathematical model has the objectives of minimizing the total severity index for the hospital subject to the constraint of staff availability by skill level, and of keeping the difference in severity indexes between various units less than or equal to a predetermined constant. The model is then solved using a branch-and-bound algorithm.

Calichman [28] presents a linear programming model to balance the bed demand among various surgical services. The objective is to maximize the total revenue subject to the operating room time availability, bed availability, and the demand for services constraints. Fries and Marathe [29] use mathematical models to determine the optimal variable-sized multiple-block appointment system.

Another use of optimization models has been in the field of epidemiology. Lee and Pierskalla [30] studied the optimal mass-screening strategies for contagious diseases that have no latent periods using mathematical models. Kaplan [31] used a mathematical model to study the AIDS epidemic.

QUALITY ANALYSIS, CONTROL, AND IMPROVEMENT

During the late 1980s, there has been a surge in the health care industry toward adoption of the various IE techniques related to quality in order to improve health care services. Many hospitals have initiated quality improvement programs (QIPs) using the concepts and tools that have already been proved successful in the manufacturing industry. These programs are based on the quality philosophies of Edward Deming, J. M. Juran, and Philip Crosby. There are some differences in these philosophies and their respective approaches to quality improvement, but there are more similarities than differences [32].

Four fundamental concepts form the foundations of continuous quality improvement (CQI). These concepts are: (1) customer focus, (2) process focus, (3) employee and physician empowerment, and (4) data-driven quality improvement [33–36]. Customer focus implies that organizations must consistently strive to understand the needs of their customers. They should design their products and services to meet these needs. A customer-focused organization forms a long-term partnership by which it continually exceeds its customers' expectations. A central theme of CQI is that improvement of service takes place in any organization by focusing on process improvements. By focusing on process improvement, organizations can continuously improve quality. Empowerment of physicians and employees to change conditions of work and to improve their work processes is the third key concept in CQI. This means workers have to be trained and given new tools so that they can perform their jobs better. Finally, measurement and data are key to process improvement. By defining key quality characteristics and by measurement and monitoring of these, a health care organization continually improves. There are multiple process improvement methodologies discussed in literature. Several of them, including FOCUS-PDCA, are discussed in Chap. 3 of the book, *Reengineering Health Care: Building on CQI,* by Griffith, Sahney, and Mohr [33].

Various charts that are helpful in process analysis and improvement are the Pareto chart, cause-effect (or fish bone) diagram, flowcharts, run charts, and control charts. An example of the utilization of the cause-effect diagram to investigate the causes of inappropriate use of cephalosporin antibiotics is shown in Fig. 15.3.2.

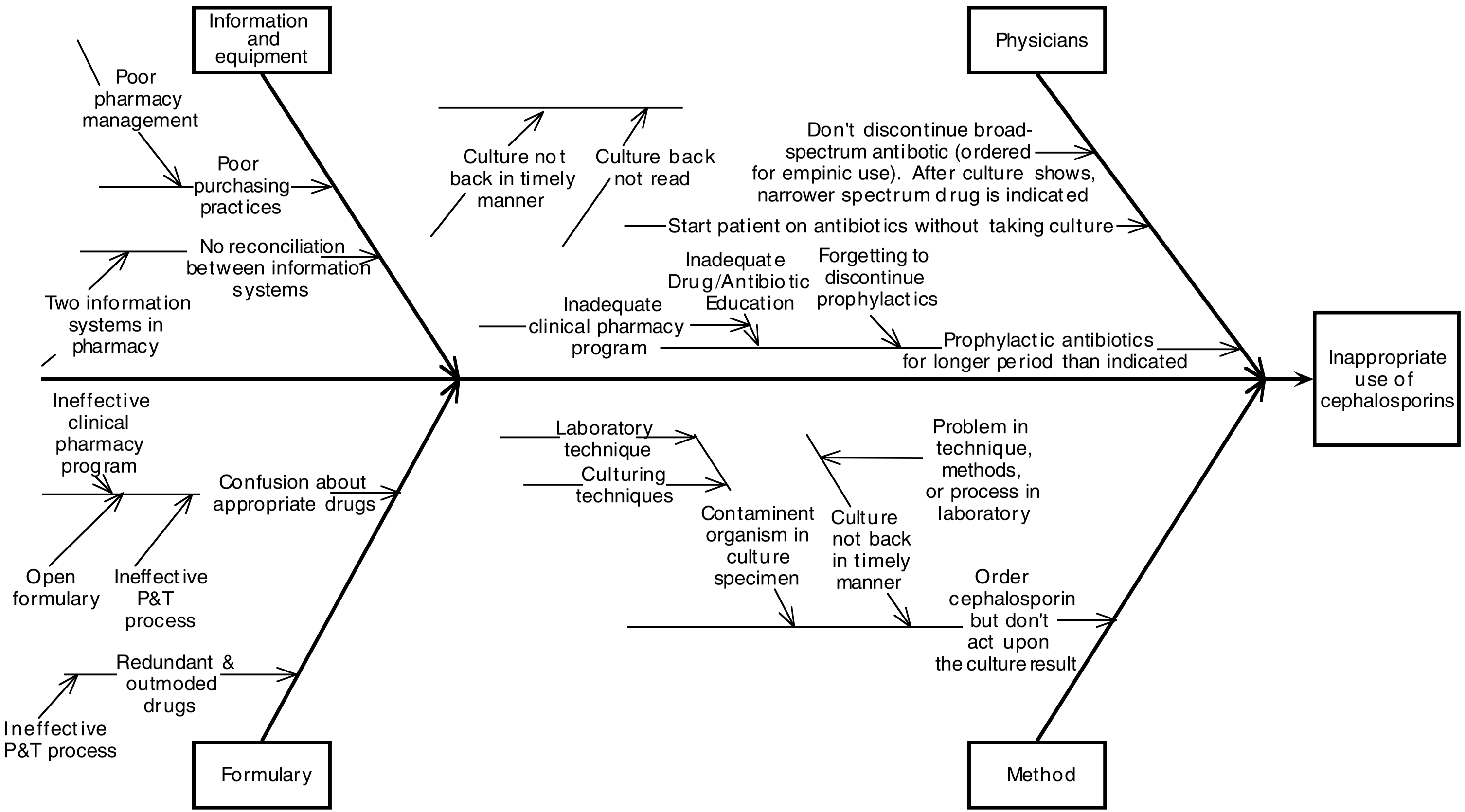
Information and equipment
Physicians
Formulary
Method
Inappropriate use of cephalosporins
Poor pharmacy management
Poor purchasing practices
No reconciliation between information systems
Two information systems in pharmacy
Culture not back in timely manner
Culture back not read
Don't discontinue broad-spectrum antibotic (ordered for empinic use). After culture shows, narrower spectrum drug is indicated
Start patient on antibiotics without taking culture
Inadequate Drug/Antibiotic Education
Forgetting to discontinue prophylactics
Inadequate clinical pharmacy program
Prophylactic antibiotics for longer period than indicated
Ineffective clinical pharmacy program
Confusion about appropriate drugs
Open formulary
Ineffective P&T process
Redundant & outmoded drugs
Ineffective P&T process
Laboratory technique
Culturing techniques
Contaminent organism in culture specimen
Problem in technique, methods, or process in laboratory
Culture not back in timely manner
Order cephalosporin but don't act upon the culture result

FIGURE 15.3.2 Cause-effect diagram to investigate the causes of inappropriate use of cephalosporin antibiotics. (*Reprinted with permission from Nackel, John, and Thomas Collier, "Implementing a Quality Improvement Program,"* Journal of the Society for Health Systems, *vol. 1, no. 1, 1989.*)

OTHER IE TECHNIQUES

Because of space constraints, the application of other IE techniques in health service cannot be covered here. We refer the readers to Sahney [37], and Goldman and Knappenberger [38]. These two articles discuss in detail the evolution of IE in health care. References listed at the end of the chapter include several articles about these applications. The areas of application in health care functions have been divided into six groupings as shown in Table 15.3.2.

TABLE 15.3.2 Groupings of Areas of Applications in Health Care Functions

Business office	Admitting, financial, billing, etc.
Nursing	
Ancillary services	Physical therapy, laboratory, radiology, pharmacy, etc.
Support services	Dietary, housekeeping, materials management, medical records, laundry, transportation services, physical facilities, etc.
Medical services	Intensive-care units, emergency rooms, operating rooms, outpatient clinics, etc.
General health care applications	

Table 15.3.3 summarizes the various references by the type of technique and the area of application in the health services. Table 15.3.3 may be used to quickly find some representative articles on the applications of a particular IE technique to a specific type of department in a hospital.

FUTURE OF IE IN HEALTH SERVICES

The environment in the health care industry has undergone significant changes in the past few years, and more are expected. For instance, health care systems are currently facing serious financial hits because of a reduction of Medicare/Medicaid reimbursements, and the simultaneous reduction in payments from health maintenance organizations (HMOs). These changes in the health care marketplace are affecting the industrial engineer's role in health care, not only in the types of assignments given, but also in the level of sophistication of tools used in performing these assignments.

Industrial engineers are increasingly being involved in projects that deal with strategic issues, such as decisions on mergers, opening new clinics, and adding or dropping a product line. They are also being used in studies involving medical judgment, such as developing protocols for patient care, evaluating clinical staff use for different tasks, or developing policies for product standardization. Administrators, physicians, and other professionals are recognizing the importance of including industrial engineers in these types of projects. While industrial engineers may not have expertise in the specific subject matter, they can analyze the impact of alternative courses of action on operations, or the financial performance of a department or business unit.

Industrial engineers are increasingly being included on project teams for information systems–related projects, along with individuals from information services departments as well as the users. Industrial engineers are great at interviewing the client department to determine user requirements. They are also good in the implementation phase, since manual processes in the client department usually require major changes during and after the implementation of an information system. Industrial engineers are also serving on quality improvement teams as facilitators or in a staff role. They are increasingly being used as full members of the teams,

TABLE 15.3.3 Matrix of Reference Numbers for Various Areas of Health Services and Applicable Industrial Engineering Techniques

	Business	Nursing	Ancillary	Support	Medical	General
Methods improvement	39		65	42, 63	44, 46	
Staffing and productivity		64, 74	45, 58	51, 76	79	34, 50, 56, 82, 86, 87, 89, 96
Scheduling	55	15, 26, 59, 81			71, 73	
Queuing and simulation modeling	21				18, 19, 20, 22, 23, 25, 43, 69, 72	24, 83
Optimization	28	14, 27, 94			29	30, 31
Human resource management and incentives			95	49, 84		62, 67, 92
Inventory management and facilities planning				16, 91	25, 54, 68	
Benchmarking and reengineering						33, 61, 66
Quality analysis, control and improvement, TQM/CQI	39	40			44, 53, 75, 85, 93	32, 33, 34, 35, 36, 41, 47, 57, 61, 87, 90, 96
Cost control, economic analysis		64			50, 77, 78	
Information systems and RFP process		74		70	16, 60, 80	48, 88

offering process and operations insights, as well as the ability to quantitatively evaluate the alternatives. These assignments require excellent communication and people skills. The popularity of reengineering projects is providing a new avenue for the use of skills and tools that industrial engineers possess.

The recent availability of reasonably priced, user-friendly simulation packages has increased the use of simulation modeling as a tool to model real systems. These models are being used to predict the impact of various policies and resource levels on the performance of the system. This trend of using sophisticated tools to evaluate alternatives is expected to continue. As health care leaders become more familiar with the skills and capabilities of industrial engineers and use them to their full potential, industrial engineers will find themselves in greater demand than ever in health services.

CONCLUSION

Industrial engineers have played a major role during the past 30 years in introducing quality and productivity management tools to the health care industry. Reimbursement systems were one of the major barriers in the introduction of IE techniques in the hospitals during the 1970s. With the changing reimbursement climate in the 1980s, increasing numbers of hospitals are paying attention to issues of quality and productivity. Many of the techniques that were the sole domain of the manufacturing industry are now commonplace in most well-run hospitals. Inventory management, labor staffing, scheduling, methods improvement, and quality management concepts are increasingly being utilized on a daily basis to improve the productivity of the health care sector.

The Society of Health Systems and the Healthcare Information and Management System Society are the two professional organizations serving the needs of the professionals in this area. Both of these societies offer joint annual conferences in the fall and winter. Attendance has grown from 100 in the early 1970s to over 15,000 in 1998, showing the growth of the field.

As health care costs keep increasing, so will the need for industrial engineers.

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CHAPTER 15.4

CASE STUDY: AUTOMATED STAFFING DETERMINATION FOR A GROCERY CHAIN

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This case study will discuss the practical design and implementation issues of an automated staffing determination project in a grocery chain. The discussion will be based on a project initiated by Dominick's Finer Foods in 1997, and will present the critical path responsible for the project's success. In detail, team requirements, measurement logic, pilot store application, standards' validation, rollout requirements, information technology requirements, and potential future use of the output will be discussed. The reader should be familiar with the Maynard Operation Sequence Technique before reading the case study. The case study does not delve into specifics of measurement but concentrates on application of principles in the retail environment.

BACKGROUND

Change as the Constant

Change is the only remaining constant in today's business world. Shareholders, customers, and employees are increasing their demands from top management. Public or private, almost every company is engaged in some kind of a project to improve value delivery systems. As the central participants of these systems, industrial engineers are expected to identify, test, and implement solutions that will generate the demanded results.

Challenge in Service Sector

The fragile nature of service companies dictates greater focus and more selective approach to potential projects. Almost every employee of service firms has contact with customers and their daily requirements. Being staffed with the optimum workforce with shared best practices is the most critical challenge in a service environment.

Because service companies must supply almost all their resources in advance leaves most executives with fixed short-term capacity and expenses, which cannot be easily amended. So, determining the staff capacity to meet the changing workloads created by fluctuating consumer demand for different products is the key component in a company's profitability.

Grocery Industry Initiatives

After recognizing the same challenges and their future implications, several participants of the grocery industry formed a committee to research potential approaches to solve aforementioned problems. In response, the committee created the Efficient Consumer Response (ECR) initiative. The ECR initiative is designed to achieve performance improvement through four core processes: efficient store assortments, efficient replenishment, efficient promotion, and efficient product introductions. The execution of ECR is determined to be in two phases: the best practices implementation and full ECR implementation.

There is not a single approach or time frame to implement ECR successfully. Since each ECR component would have different demands from the daily functions of a grocery store chain, analyzing the existing structures and commitments in designing an ECR project is the most viable approach.

Dominick's Finer Foods, Inc.

Dominick's Finer Foods (DFF) is a grocery store chain based in Northlake, Illinois. With its 112 stores and 17,000 employees, DFF faced the same pressures and changing environment as the rest of the market. To create an organizational plan to address these issues, DFF's management initiated a project to implement some components of ECR's best practices phase. In July 1997, a team of consultants and an internal DFF team launched the industry best practices element of the project.

One of the most critical parts of the project was determining the labor requirements of the new store environment under which DFF would operate. To this end, Maynard Operation Sequence Technique (MOST®) was identified as a viable option. The following sections describe the evaluation approach and implementation lessons learned during this period.

PROJECT DECISION AND EVALUATION

Shifting to an Integrated Solution

At the time of the decision, DFF already had an automated labor-scheduling program. The program was implemented in 1990 based on a labor-scheduling project. The project utilized work-sampling methodology to calculate time values that represented the average time required to perform certain tasks within DFF's stores. So custom sets of work standards were developed for given store environments.

However, since 1990 there have been several changes in different areas of the business. Store layouts have changed dramatically. The number of store formats increased and the Fresh Store concept changed the composition of available departments. There have been significant improvements in the available technology both at the front- and back-store operations. The workforce is different, due to changes in the labor market: The tightening of the labor market changed the skill set available to employ, leading to changes in the employee qualification and training practices.

Despite these changes, the scheduling was accomplished through the original time values established in 1990. Given the further changes expected as a result of the best practices project, a new, more dynamic integrated solution was needed.

MOST as an Alternative

The project team identified MOST work measurement and computer systems as the solution to set engineered time standards. MOST work measurement system uses predetermined time and motion studies to create time standards for a given sequence of method steps. Since the system is based on creating suboperations that are measurable parts of an operation, with any change in a given environment, changing respective suboperations would be the only update needed for the time standard to be accurate. With the MOST computer systems this procedure is simplified further. After the initial effort to set the time standards, a dedicated internal industrial engineer can monitor the changes and update the standards easily. Further, standard setting for multiple stores with their respective differences can be executed quickly by using AutoMOST, a knowledge-based expert system.

PROJECT PLANNING AND EXECUTION COMPONENTS

What to Measure? Measuring the Best Sequence of Method Steps

The benefits of using accurate time values are significant. However, the real return from this effort comes when the measured sequence of method steps is the best among all alternatives. In almost all organizations, one can find better methods to complete the same task. This is possible due to changes in technology or simply because organizations may get used to operating with the same inefficient processes over time. Thus, identifying the best business processes and then creating the respective time values would be the desirable approach. For some organizations this approach may not be the realistic sequence. Internal dynamics and management priorities may dictate a different project logic. In these cases, identifying the total project scope and dividing the project into multiple phases and their respective roles would be helpful in setting organizational expectations.

The positioning of a project's measurement phase is very important. Acceptance and utilization of the work standards will depend on the initial success of the project communication with related parties. Communicating how the measurement phase fits into the greater goal would clarify the expected output and its dependencies. Additionally, it would give time to the project sponsor to make organizational adjustments before starting other phases of the project. For some companies, the need to change will become more apparent after realizing the true cost of using the old processes. Creating a baseline for current process costs would provide the needed cost-benefit calculation. Having a larger base of agreement for the need to change would increase the project's chance of successful execution.

Who Should Be the Project Sponsor?

Staff planning is a controversial issue in many service industries. In labor relations there are multiple parties with different beliefs and interests. The measurement logic of work standards would attract these parties' attention as soon as the project announcement is made. A project that intends to change the approach to staff planning should be given top priority because of its implications on an organization's culture.

The project sponsor's organizational and power position is critical in signaling top management's intentions. A high-ranking project sponsor would communicate the weight and importance of the project. Since everybody in the organization will be affected by the project, the project sponsor would play the role of the initiator. He or she has to show determination and good understanding of all parties' concerns. The project sponsor must address all concerns and have the authority to institute the necessary changes to solve them.

Choosing the Project Manager and Team Members

Another critical, if not the most important, step in the planning stage of the project is forming a team of experienced department managers and selecting a project manager. The project manager position is one that requires prior project management experience. The manager will need to bring together and create a cohesive unit of department managers and provide resources required by the team members. He or she will be the ultimate person to address any questions regarding the project progress and execution. In addition to managing the team members, he or she may need to give the decision to bring outside consultants to complement team members' skills and expedite the project's critical segments. Integrating consultants to the team and creating a tension-free work environment would be the initial responsibility of the manager. Since the project would require participation from multiple disciplines in the organization, managing the timeline to meet multiple priorities would be part of the manager's responsibilities.

One of the notable dilemmas in the project manager selection process is whether to assign a project manager from within the company or bring in an outside consultant. Each alternative has its pros and cons and the decision should be based on the organization's unique position. Some of the arguments for choosing a manager from within the organization are an individual's specialized knowledge of the organization and participants, and his or her experience in working with different departments and developing an insider for future projects and top management positions. The benefits of hiring an outsider as the manager can be summarized as experience in managing complex projects, unbiased approach to issues and participants, unique perspective on the organization's specific problems, and minimal change and disruption in daily workload of internal executives.

After the project manager assignment, a more critical step is to identify department managers that can work in a team environment. The department managers must be selected from the top performers. They should have a good reputation and high level of trust among their colleagues. The credibility of the project output will depend on the department-level participants since tasklists and method steps will be developed and validated by the department managers. It is crucial to have managers who are familiar with companywide processes and are approved by top management.

It is unrealistic to expect all participants to understand the team dynamics. At the beginning phase of the project, conducting several workshops to address teamwork principles, project-oriented decision making, working with deadlines, and conflict resolution would be beneficial to create a more productive environment. Even though initially all members will not need to work together to complete the measurement phase of the project, validation and rollout phases will require greater cooperation. Additionally, the team will be ready for other follow-up phases and projects that can build on the automated staff determination project.

MOST Computer Systems Developers and Applicators

The question of who will ultimately be responsible for maintaining and using the project output determines the identity of MOST and AutoMOST developers and applicators. The number of developers and applicators depends on the company size and planned project turnaround time. In this case, DFF had two developers and one applicator. Additionally, four DFF employees participated in the training sessions and received certification. Having at least one person act as a developer and applicator is critical, so dedicating an industrial engineer from the beginning of the project to learn, develop, validate, and implement the standards is necessary. All developers and applicators must complete their training and certification before the measurement work. This will ensure a high-level understanding of the system that is necessary to communicate with all parties. The same personnel will also be responsible for executing subsequent integration of the MOST modules to the existing systems. Transition to the new program will not be delayed due to misunderstandings of each system and their respective requirements from the organization.

Selecting a Pilot Site

In a grocery store chain, multiple store formats with different departments and categories can be available. This leads to another critical step in the project: choosing a representative pilot site. At the initial stages of the project, an all-inclusive store format would be preferable. If the management has long-term plans to shift store layouts and department offerings to a certain store format, then choosing the model of the future will have certain advantages. In addition to physical comparison benefits, there will be category planning implications.

Plan Rollout Before the Measurement

It is only natural to expect different rumors about the project to travel between stores. Eliminating the misconceptions about the project would have significant positive impact in the rollout phase. Obtaining support from the department managers during the initial development phase would depend on proving the practical aspects of the MOST principles. Until comfort with the methods and tools of the project has been established, full commitment cannot be expected. Getting a high level of commitment from participants would provide the necessary communication channel to the rest of the chain.

In a store environment, there are several departments for which results are easier to measure and communicate. Starting the measurement phase with one of these departments would provide the team a better opportunity to understand project measurement principles. In our experience, nonperishables departments are relatively easy to measure and validate. In these departments, the variations in the processes between stores are minimal and personal interpretations of the methods are closer. As a consequence, preparing a complete demonstration of a single department such as a grocery department would be possible to do in a relatively shorter period. If during the presentation, understanding on principles of predetermined time and motion studies can be achieved, the following measurement and validation tasks would be easier.

Project Timeline

There are six distinctive phases in the automated staffing determination project: decision, planning, measurement, validation, integration, and rollout phases. The decision phase involves identification of project sponsor, project manager, and calculation of return on investment of the project. After project approval, in the planning phase, developers, applicators, and team members are selected with the help of the human resources department. If need is determined, outside consultants would be screened and tasked. Site selection and all training functions take place during this phase. The decision and planning phases can be completed in 2 to 3 months.

The duration of the measurement phase would vary depending on the number of departments in a store, number of different store formats, and identification of companywide processes. In DFF, the measurement phase lasted 12 weeks. This period did not include any time to extensively review or improve any processes or methods. Twelve weeks were dedicated to measure department standards. These departments were front end, customer service desk, grocery (including frozen and dairy), general merchandise, deli, produce, meat and seafood, bakery, floral, cafe, and liquor. AutoMOST decision tree development and integration is not included in this time frame.

The validation phase involves reviewing and verifying the standards and their associated time values against reality. Since this is the last opportunity for the team to review the standards in detail before putting them into work, this stage of the development is very important. Validation phase can take 3 to 4 weeks.

Multiple departments will perform the integration work. At this phase, the information technology (IT) department's role is critical. Mapping the current system and identifying current locations of the standard drivers such as percentage of customers using cash, number of cases shipped per week, and so on are necessary to build the base for the new system to run. Successful implementation of the system depends on the available technical resources. The best way to address this point is to establish communication with an assigned IT resource on a weekly basis during the measurement phase. Meeting once a week to inform the representative on the driver requirements for each completed department would initiate the work sooner and mapping can be completed in time for integration. Other IT department priorities may sometimes force the project to halt for extended periods, causing the project to lose its focus. As a consequence, the organization's trust in the system would be affected as well.

During the integration phase, the rollout schedule would be developed and approved. Roll out of the system to each store can take a long time. In our case, each store required 2 to 3 days of systems review. Therefore, the project can be completed for a chain of 100 stores in a year. Before turning the system on, testing communication channels between stores and headquarters should be done. But this concerns mainly IT resources.

Task Identification

The first step in measurement is to identify every possible task in a given department. In MOST terminology, a task is an activity. An *activity* is defined as a series of logical events that take place when an object is moved, observed, or treated by hand, a tool, or a transportation device [1]. Since our goal is to staff departments based on expected workload, we need to cover all possible tasks in a period. Department managers should be interviewed after a brief explanation of task, operation, and tool terms. The most critical concept to communicate is that even if the task seems like a minor one, it should be included in the list. The most effective way to explain the consequence is to emphasize that unless a task is listed, no time will be associated with it toward the staffing of the department. It should be clear that the task list document would be a work-in-progress document. At every observation of an unlisted activity, a new task should be added to the list; department managers must be alert for initially missed tasks.

Method of Measurement

Every task in the list cannot be and should not be measured with MOST. Certain tasks include some subactivities that cannot be easily standardized. Phone conversations and customer interactions are some of those difficult-to-measure activities. The next logical step is to identify the task measurement method. From several alternatives, there are three effective measurement approaches in a grocery store environment: MOST, time study, and benchmarking. Each task should be assigned a measurement method based on the importance, frequency, and nature of the task. Since collecting a statistically significant number of observations would take considerable time, time studies should be designed and scheduled to start immediately and continue in parallel with the MOST measurement.

It is important to note that some activities are fixed, while some are variable. If an activity is performed regardless of the customer volume and is necessary to meet the required corporate and legal standards, it can be categorized as a fixed activity. However, if the same activity can take significantly varying time values in different stores, then the activity should be categorized as a variable activity. A good example is the cleaning of produce tables. Even though the frequency and the time value of the cleaning activity is fixed for the pilot store, the activity should be categorized as variable and measured with MOST. The total length or shape of produce tables in other stores may be different leading to varying time standards to accomplish the same task. Generally, most setup functions, low-frequency activities, and all management functions such as scheduling or staff meetings can be categorized as fixed activities.

Calculating the fixed hours gives more information about a department's cost base. In certain departments such as seafood, fixed labor-hours should be compared with the total hours the department is open before making a determination. If the department needs to be open more than the combined fixed and variable hours for the department, then open hours need to be treated as fixed hours to meet the constraint. In DFF, the seafood department was open 90 hours a week. The system calculated seafood department hours for a representative week was close to 50 hours. The recommendation then was to use the 90 hours until the system-calculated department hours exceeded the open hours.

Measurement of fixed activities can be accomplished with time studies, expert opinion, or benchmark information. Even though benchmark information is useful, it should be analyzed with respect to applicability to the store environment from a physical constraint perspective. Some fixed activities are based on established corporate rules and strategy. In a service environment most activities have service implications and the upper management can identify these activities to differentiate its stores from the competition's stores by focusing on those activities. The measurement of those activities should be done from the corporate guidelines containing description and frequency. However, using the benchmark information would be useful from costing and marketing planning perspectives. A comparative cost-benefit analysis using comparative benchmark data, corporate strategy data, and a customer service index would establish a clear return on investment in these identified activities.

At the end of this stage, a comprehensive task list, including nature of each task, unit of measure, and associated method of measurement should be in place to start the measurement process. As an example, "checking out a customer at front end" is a per customer (variable) task, and should be measured with MOST.

Measurement

Measuring activities with MOST requires preparation of detailed method steps for each activity. The developers should prepare the method step sheets by interviewing and observing department managers during the activity. An alternative approach can be to videotape the activity and simulate it later. After the initial draft for each activity, the department manager should review the method sheet. In the method sheet, equipment and tools used must be included. For all equipment used to perform the task, model, brand, and machine operating times need to be obtained and noted. During the rollout phase, as different models of the same equipment are used in other stores, new machine operating times need to be established. Machine operating times can be established with stopwatch studies. However, using a stopwatch overtly could be a sensitive issue. When used, it should not be displayed as the mechanism for activity measurement but machine operating time only.

The detail of method steps required depends on the work measurement technique selected for the suboperation or activity. In a grocery store environment BasicMOST or MiniMOST can be used. The decision should be based on the character and frequency of the activity. BasicMOST can be used in most of the suboperations in the grocery setting. However, for high-frequency and short-duration operations, MiniMOST would provide more detailed and accurate time values. In grocery stores, there are certain suboperations such as cutting a box, stocking, blocking, and data entry that are used by multiple departments in high frequency that should be measured by MiniMOST. In MiniMOST, distances, equipment location, and condition have greater impact on accurate time standards. Thus, observation and simulation of the activity may be needed to have a better understanding of the method steps.

Before the direct measurement, completing the initial version of the task lists and method steps is necessary. Gaining a full picture of the departments and respective operations would drive the suboperation development rationale. The development would be more effective when used in conjunction with H. B. Maynard's top-down technique. The top-down technique dictates understanding of all operations in their environment and planning to minimize the number of suboperations created for the measurement and still maintain the desired level of accuracy. In a grocery store, the same suboperations can be used for multiple operations in different departments. Development time of the suboperations and operations will be based on the initial planning done to analyze the operations and their steps.

Measurement with MOST for Windows in grocery stores utilizes the preceding principles. Therefore, an experienced developer should have little difficulty in creating suboperations and operations. The most difficult component of the measurement is identifying respective suboperation frequencies. As an example, within the "check out customer at front end" operation, a certain percentage of customers will use check as the payment method. In this operation, the "accept and process check at front end" suboperation will need to be given a frequency. Eventually this frequency will be provided by the IT department in the driver database. In the meantime, an estimate established with a preliminary study can be used.

Establish Allowance Rationale

Allowances are applied to each operation to cover time for personal needs, fatigue, and unavoidable delays. In addition to these, there can be special allowances for different departments to cover unique environmental effects or conditions. Allowances can be established from industry data, benchmarks, or time studies. Most of the employee concerns in the store will be regarding unavoidable delays due to customer questions or some other factor in the store. Developing and using a sound allowance rationale would assist the team members in communicating the steps taken to address those situations. Top management should review and approve the allowance factor to eliminate misconceptions further into the work. In DFF, the allowance factor used was 15 percent, unless a special allowance was requested for a particular store.

Data Hierarchy

At the completion of the measurement phase, there will be multiple levels of information in the database: suboperations, operations for all departments, a plan for each department, and a group of plans for each store. In the DFF project, the total number of suboperations created was 168. The number of operations in a department varied from 3 to 24. Examples of operations include "issue gift certificate at customer service desk," "stock case at grocery," "blocking in dairy," "write frozen meat order," and "cull deli cheese case." Each of these operations has a time standard with different units of measure. For example, the "stock case at grocery" standard applies per box. By multiplying each operation with respective frequencies for a given period, the plan-level time standard is calculated—to stock 5000 cases a week, the grocery department needs to staff $5000 \cdot x$ hours, where x is the time value of "stocking one box."

Plan-level measurement will provide a department's required number of staff-hours to complete the expected level of workload. With changes in the workload expectations, total department hours fluctuate. To obtain total store hours, department plans will be added. Further categorization is possible to calculate labor-hours for a cluster of stores or the chain. AutoMOST could be used for this task to expedite the standard generation and aggregation of different pieces of information.

Validating the Standards

The measurement phase will be completed for the pilot site with the development of the store-level plan. However, all standards measured still need to be validated. The validation phase can be designed to answer two questions: (1) is the standard at hand correct from process steps and time value perspective for the pilot site, and (2) are there variations of the standard between different store formats? The validation needs to be administered by team members other than the developers. This phase is the last opportunity to amend the time stan-

CASE STUDY: AUTOMATED STAFFING DETERMINATION FOR A GROCERY CHAIN

dards for the pilot site and other stores of the same format. The level of validation detail changes the duration of this phase and should be determined by the project manager. Rollout planning can be initiated at the same time to include the findings and anticipate other potential problems during the rollout.

Identify Differences Between Stores

Following the measurement and validation of the pilot store operations, differences in the operations for other store formats and clusters need to be identified. There are two main reasons for an operation to have different method steps at different stores: physical and equipment constraints. Both of these constraints can be identified without visiting the stores. If updated store layouts and detailed equipment lists can be obtained, a majority of the work can be completed before visiting the stores. From the store maps, necessary distances can be measured and incorporated to the standards. For different equipment, new machine-operating time measurements need to be obtained. However, this is an easy task and requires a single visit to the store with the equipment.

Rollout phase staffing requirements and duration can vary with the level of work that needs to be accomplished. From a work measurement perspective, unless the management is planning to have all stores follow the same standards in the same departments, the work explained previously needs to be repeated for each specific store. However, the benefits in standardizing the operations should eliminate this scenario. Even though the decision to follow the same standards exist, updating the standards with changing frequencies and workload expectations for all stores needs to be executed.

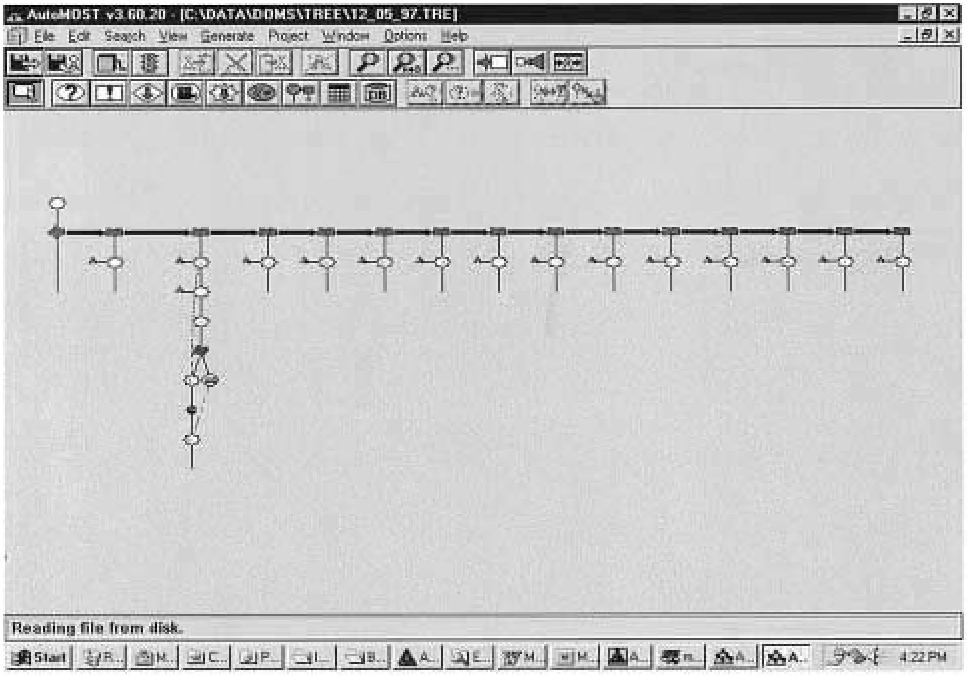
Automating Standard Setting for Multiple Stores

At the end of the measurement phase, an average grocery store with 14 departments would have close to 180 operations and 14 plans. If a grocery chain has 100 stores, assuming staffing determination will be calculated every month, 18,000 operations and 1400 plans will need to be updated. Considering the frequencies in the operations as well, this task with manual entry would be significantly burdensome to perform in a short period of time.

One of the components in the MOST program is AutoMOST. AutoMOST is an expert system that can be integrated with other modules to update operations and plans automatically with provided driver frequencies. The decision to use AutoMOST from the beginning of the project can reduce the time spent for the standards automation. Since AutoMOST can generate the standards in the MOST Data Manager module, which houses the operations or time standards, design of the decision tree can be performed during the measurement phase, and additional AutoMOST development time can be avoided. However, this may add some time to the measurement phase to test the logic of the decision tree.

In AutoMOST, multiple designs of nodes can be used in the decision tree to achieve the same outcome. The path followed for DFF used procedure nodes for different levels. A store was identified as a procedure node with all the departments as its separate branches. And each department under each branch also had another procedure node with all operations under a separate branch (see Fig. 15.4.1). When the AutoMOST decision tree is run, it calculates hours for store 1, then 2, and 3 and updates all the operations and plans until it reaches the last store. When the last store is run, all department hours for every store are collected in an Excel spreadsheet to be fed into the scheduling program. The data is programmed to flow to calculate department, store, cluster, and total chain hours.

Designing the data flow to feed the decision tree with driver frequencies for 112 stores is very important. The platform used for DFF was dBase (.dbf) files created through Excel. For every department a separate .dbf file was created and each store had a row dedicated for its drivers. Within a single Excel file there were multiple workbooks set for all drivers, fixed


AutoMOST v3.60.20 - [C:\DATA\DOMS\TREE\12_05_97.TRE]
File Edit Search View Generate Project Window Options Help
Start
4:22 PM

Reading file from disk.

FIGURE 15.4.1 AutoMOST logic tree—Dominick's Finer Foods, Inc.

drivers, variable drivers, and driver explanations. The files were the primary communication base with the IT department since the drivers needed to be located for each store, mapped, and fed into the Excel files automatically for periodic updating of the standards. Initially, mapping the drivers and deciding on the method to populate the files takes some time. However, once established, the channel would not need further design work by IT and the project participants.

The most important point to remember is to assign an IT resource from the beginning of the project to locate, map, and populate driver information. Since the drivers will be identified throughout the measurement phase, creating the driver libraries before the end of the validation phase would be possible. At the same time, integration work between the existing and new staffing programs can be accomplished as well. As soon as the files are populated and integration of systems is completed, staffing determination for the stores can begin. Turning on the system in real life would be pending the complete test of the system.

Rollout Period

Turning on the system requires multiple level tests. Starting with one store in each cluster and testing the system output versus current staffing schedules should be the initial check to understand transition period implications. The departments with high variance should be identified and main causes should be explored. Developing a project binder to explain the methodology and answer common questions will be helpful. Using uniform responses to multiple parties will increase the confidence to the system. Special attention should be given to method step conformity. If employees follow different steps for an operation than the one measured, associated time value will not reflect the work involved, leading to problems in the store. These problems can have significant impact on the customer perceptions since it will immediately affect the work completion rates. Incorrect scheduling of front-end staff increases the lines and the time to check out a customer. Unfinished loads would increase the number of out-of-stock items, disrupting the service provided in the store. A store's regional and demographic effects on the driver frequencies should be monitored, as well. Necessary adjustments are easy to make since the system is based on a top-down approach.

SYSTEM MANAGEMENT AFTER THE PROJECT

Central Information Management

The corporate division that will be responsible from setting the staff schedules using the new system will need to operate like a central information pool. Every change planned at the store and department level will need to be communicated to the division and industrial engineers responsible for the maintenance of the system. Implementation schedule of the changes will need to get approval from the division since the staffing will be affected by the changes.

The industrial engineers will be responsible for making the necessary suboperation- and operation-level changes in the system. Additionally, the decision tree will need to be updated to reflect the new standards. By using the division as the hub of chainwide information, integrity of the system will be maintained. This will ensure that no other major staff determination project will be needed. With small modifications, the next schedule will reflect the new store environment.

Project Assistance

One of the valuable capabilities of the system is being able to simulate impacts of potential projects to the store environment and the chain. With the discovery of this capability, requests for assistance to special projects would increase. Management of these requests must be organized and the database should be guarded against pollution. As a security mechanism, the system's developer version and system administrator functions should be assigned to a certified developer and applicator. Setting the passwords and access authorization to multiple levels needs to be monitored.

POTENTIAL USES OF THE SYSTEM AND DATABASE

Project Valuation

The system can be used to calculate the return on investment of any new methods, equipment, or format changes. Since the operations at department level are based on suboperations that can be modified, comparison of the same operation with the new method or equipment would provide the net gain/loss from direct labor perspective. Additionally, since machine-operating times are recorded, transaction time comparisons or equipment utilization ratios can be established.

The real benefit of the method-step approach would come when the project is coupled with an industry best practices application. Making improvements to the current processes and increasing the work efficiency and throughput would be the natural outcomes of a combined project. Rather than implementing and going through the change management cycle with unclear returns in mind, the project team can simulate the virtual environment based on proposed best practices with the MOST system. The substantiated benefits could increase the support to the project before implementation. Having the upper hand on financial information in an age of expectation management would be beneficial for any top manager.

Activity-Based Costing

Having correct cost information is the leading indicator of having correct financial information. Activity-based costing (ABC) is one of the most recent costing approaches to address this area. The driver libraries created with MOST can be utilized in an ABC project. The activities are the base of costs at different levels, and each activity requires different resources. In a service environment, applying ABC can be expedited through the use of the standards in the database.

Efficient Consumer Response

Efficient Consumer Response is an initiative to improve the grocery industry's responsiveness to the changing environment. One phase in the ECR is computer-assisted ordering (CAO). In CAO, a program using historical movement data, seasonality factors, and a calculated trend calculates the orders. As a result, for each item based on specified categorical rules, an order is placed to the warehouse to be delivered in the next delivery window. Each product ordered generates work that needs to be performed. By integrating the CAO software modules with the database to populate the driver frequencies, one can determine real-time staffing requirements. Practicality of the matter needs to be further studied but potentially the system can be refined in more ways.

Compensation Incentives Program

Predetermined time and motion studies are based on 100 percent skill and 100 percent effort level. All the standards developed assume that all employees have the necessary skills and desire to perform their tasks. Although it can be argued that financial benefits may not be the most important incentive for an employee, generally compensation tied to performance is accepted to be the most effective incentive system. However, in every case, top management runs into a problem of identifying a baseline that all parties would agree to peg the performance measure against. The staffing determination project essentially sets the baseline for an employee with 100 percent skill and 100 percent effort. If acceptance by all parties can be obtained, a performance-based incentive program can be instituted.

CONCLUSION AND FUTURE TRENDS

In an industry with accelerating consolidation, the most significant differentiation point for any grocery chain will be its employees. The industrial engineers will be asked to develop original solutions to problems with greater implications. As outlined in this case study, some fundamental questions need to be addressed before any type of staffing determination project can be initiated: How dynamic will the outcome be? How long will the company be able to use it? How much pain do we need to endure to reach our goals?

The progress in the business technologies will require all companies to update and improve their current capabilities continuously. The company that anticipates the future while designing its technological infrastructure will be the winner. Planning and executing a staff determination project from this perspective is the most significant consideration for any industrial engineer that will be part of it.

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BIOGRAPHY

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Source: MAYNARD'S INDUSTRIAL ENGINEERING HANDBOOK

CHAPTER 15.5

CASE STUDY: DEVELOPMENT OF JOB PLANS IN AN ELECTRIC UTILITY

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In 1879, Thomas Edison perfected the incandescent lightbulb. Thereby, he provided the spark for the present-day electric utility industry. The lightbulb transformed America into a maze of wires that interconnected each of us into an electric grid, which is the source of reliable electricity. The electric utility industry is presently evolving from a monopoly to a competitive industry. The effects of deregulation are as significant as Thomas Edison's lightbulb. Competition has opened the last of the monopolistic doors. To stay in business, the electric utility must continue to provide reliable electricity with a new component: competitive rates.

A new work management process was implemented at the New York Power Authority's Niagara Power Project located at Niagara Falls, New York. This chapter will discuss the development and implementation of a work management process, which incorporates method-based work standards for the Niagara Power Project's Lewiston Pump Generating Project (LPGP). The work management process is a continuing effort of the New York Power Authority to improve productivity and lower operation and maintenance costs to meet the demands of high-quality, low-cost electricity.

BACKGROUND AND SITUATION ANALYSIS

The Creation and Evolution of the Electric Utility Industry

When Thomas Edison perfected the incandescent lightbulb, the glow from Edison's bulb demanded the creation of the electric utility industry. The birth of that industry evolved from unregulated, investor-owned power companies that serviced big business and the affluent. Each power company owned and operated generation and distribution lines. Each local power company determined the customers' voltage and frequency. The distribution poles had row after row of electric lines, both ac and dc voltage. Often electric lines came down and injured or killed people. The responsible power company did not come forward immediately. Several electric companies serviced the same city block of businesses and private homes. A lightbulb would work on one block and blow up on another.

The future held standardization. Rural America looked and waited for their power company. None came. Chaos continued.

The U.S. federal government initiated its governing powers. The regulated electric power company was born: franchised territory, guaranteed rate of return, standard voltages and frequency. In return, the electric power companies provided all customers in their franchised territory a share of their electricity at reasonable rates.

President Franklin Roosevelt's New Deal created the Rural Electrification Agency. This initiative wired the Tennessee Valley and the Pacific Northwest to provide distant customers with expensive transmission lines that otherwise would not have been built. The new transmission lines provided new customers with low-cost electricity.

The Establishment of New York Power Authority

During this period, New York State planned to harness the capability of the St. Lawrence and the Niagara Rivers for hydroelectric power. The electrification of rural New York began. The 1931 Power Authority Act of the New York State Legislature created the Power Authority of the State of New York (the name was changed in the mid-1980s to New York Power Authority [NYPA]). NYPA harnessed the St. Lawrence and the Niagara Rivers to provide electricity at affordable prices for new customers who lived and worked far from major load centers.

NYPA now owns and operates seven hydroelectric, fossil, and nuclear power generating facilities throughout the State of New York with an installed capacity of over 7000 megawatts.

Deregulation—Reasons and Consequences

The very customers who could afford the cost of electricity in the early 1900s are on the forefront demanding their right to purchase power from any energy provider. Businesses, big and small, demanded lower energy costs. Their demands required electric utilities to improve all aspects of their business to provide electricity at its lowest cost and continue to provide the quality and service reliability that consumers have learned to expect. Successful utilities will be in a commanding position in tomorrow's electricity marketplace.

The management of NYPA challenged its hydro and fossil maintenance staffs to more than double direct labor utilization and trim 15 percent from their operation and maintenance (O&M) budget. Management foresaw the bulk of O&M savings resulting from maintenance improvements with initial reductions of outside contract labor.

Traditional Planning Prior to Deregulation

Past practices were the norm for planning and scheduling work—the work content and work method passed from supervisor to supervisor. Experience estimates reflected the work content of a job, and included the myriad of time delays that typically delayed a job. Time delays are associated with, for example, materials not being delivered to the jobsite, craft labor arriving late to the jobsite, a crane not being available, operations not releasing the equipment for two extra hours, or inefficient management processes.

To improve planning and scheduling, the job plan's labor-hour estimate should include only the labor-hours required to complete the job. Once the job is scheduled, management processes are implemented efficiently to allow the completion of the work in accordance with the estimated labor-hours.

Why Job Plan? What Is a Job Plan?

A job plan is a detailed description of work with the ultimate goal to improve the craftsperson's utilization. The job plan is broken into operation steps (similar to a work breakdown structure). One operation step defines one work step required to complete the work. An operation step defines clearly an element or a piece of work, its duration in hours and minutes, and its crew size and crew composition. Any combination or number of operation steps constitutes a job plan. Typically, a job plan includes safety descriptions, parts, labor, and tools necessary to complete the job. A job plan is a formal document that defines clearly the specific work content and the required resources to complete the work successfully within its estimated labor-hours and duration.

A job plan provides the planner the ability to spend time planning the work. The planner can think about what resources will be necessary and available, how the job will be performed, what work method will be the best method, and what specialty craft and equipment will be necessary to complete the work. The planner estimates labor-hours, crew size, and crew composition requirements with a specific best-work method to complete the work.

With work content, method, and resources objectively determined, the planner will schedule the work. Upon completion of the work, feedback will be incorporated into the job plan to further improve the job plan's estimated work method, work crew size, labor-hours, materials, and tools. With successive use of the job plans, the craftsperson's utilization will continue to improve.

Definition and Components of Job Plans *After* Deregulation

NYPA chose method-based work standards to estimate the job plan's labor-hours to perform the work for the LPGP unit overhaul program. The program will overhaul the remaining 6 of the 12 hydroelectric turbine generators that have successfully pumped Niagara River water into its reservoir and generated electricity predominantly at peak electricity demands during the last 35 years. In 1998, unit 4 was overhauled; unit 8 was overhauled in 1999 and unit 7 in 2000 and one additional unit will be overhauled during each successive year. Unit 2 is presently being overhauled.

The job plans for LPGP unit 4 estimated labor-hours, work duration, work crew size, and crew composition determined objectively from the method-based work standard methodology. Since the job plans were built from the method-based work standards, without built-in time delays, the job plan was a detailed estimate of the work task that enabled NYPA to schedule the work and measure productivity improvement accurately. The standard is superior to other estimates because the estimated labor-hours reflect human motion studies and equipment process times unique to NYPA's work methods. The standard's estimated labor-hours included job safety, setup, job preparation times, and travel time associated with the work.

OBJECTIVES AND SCOPE

The Job Plan Objectives

NYPA contracted the services of a consultant to develop method-based work standards and their associated operations, and suboperation steps that were utilized in the job plans for the LPGP unit 4 overhaul. Standards were built in the same format as job plans, which included one or more operation steps. The operation steps were built from suboperation steps.

The consultant supported the following objectives:

- Developed computerized method-based work standards and associated operations and suboperations for 80 percent of the estimated labor-hours to complete 10 LPGP unit overhauls
- Determined optimal crew size and crew composition
- Provided structured maintenance management processes to implement job plans
- Identified time delays during the LPGP unit 4 overhaul and provided recommended resolution of identified time delays

- Developed a method-based work standard database with operations and suboperations for the NYPA planners to build new job plans

Expected Impact of the Standards on NYPA's Operation and Maintenance

Through a carefully designed strategy, NYPA plans to obtain significant O&M cost reductions from job plans that were developed from method-based work standards. The decision to develop method-based work standards was purely economical. The expected rate of return on the investment is maximized when the maintenance work is large and repeatable in scope. The probability that the rate of return will exceed 15 percent is greatest if the work task occurs in a well-defined scope of work and the work task occurs in a well-defined work area. Therefore, O&M cost savings would be achievable on a continuous basis in the form of measurable utilization improvement. For example, a $100 million O&M budget (excluding fuel, debt service, and the like) would typically include $80 million for direct labor costs. For this example, the expected return is $12 million for every year the utility is successful with managing the utilization improvement from 40 to 46 percent (for an average electric utility).

ORGANIZATION OF PROJECT

Project Implementation Team

The project organization consisted of joint NYPA and consultant teams to implement the new formal structured maintenance program for the LPGP unit 4 overhaul. The implementation teams

- Determined the labor-hour expenditures for the previous LPGP units 5 and 6 overhauls
- Obtained the Niagara Project management support for the program to reduce the likelihood that the program was imposed from headquarters
- Developed the implementation plan
- Included full-time dedicated Niagara Project personnel, who represented the key stakeholders in order to ensure broad-based ownership of the program and results
- Established the program benefits
- Developed a viable database
- Communicated, maintained, and supported the program

Team Management

An NYPA team manager led the team. The team manager had over 25 years experience in O&M, engineering and design, and project management. Since the program needed buy-in with craftpersons, supervisors, and superintendents within an operating power generating facility, the team manager required extensive experiences with the project to understand their O&M perspective. To maximize buy-in by all members, the team manager allowed time for the team to learn and understand the system.

Project Teams

A number of decisions were required throughout the project. The decisions ranged from selecting the best options to serve NYPA's long-term business strategy to details associated with work methods, safety practices, equipment use, and accounting practices. The ability to make decisions governed the project's schedule and cost. The chosen philosophy employed action as information and facts became available, and as the team members became more skilled in understanding the work management process.

Three teams were established: steering committee, software systems development-integration team, and method-based standards team. The steering committee members were Niagara Project management, the manager, and the consultant. The software systems development-integration team members were NYPA and the consultant, who customized AutoMOST[1] and developed and implemented the integration of MAXIMO-AutoMOST.[2]

The full-time method-based work standards team consisted of NYPA's subject matter experts (SMEs) and the consultant's knowledge engineers. SMEs were the best of NYPA's craftspersons. The SMEs developed the work breakdown structure or the top-down approach, described the best work methods to perform the work, and estimated the labor-hours necessary for each operation step of the work. The top-down approach provided the knowledge engineers with all operation steps required to overhaul the LPGP turbine generator. The detailed work method statements included work performed by craftspersons, safety precautions, job setup requirements, and required tools and equipment to complete the work.

The simplest and most complex of work methods were evaluated by the knowledge engineers to determine the proper estimating structure. This approach created a method-based work standard database with the smallest number of suboperations and operations. The knowledge engineers calculated the estimated standard time to complete 80 percent of the labor-hours associated with the LPGP unit 4 overhaul with the use of their time motion study database and NYPA's equipment process times. Comparative estimating techniques increased the standard coverage for similar work.

The knowledge engineers observed LPGP unit 6 work in progress to validate their labor-hour estimates in method-based work standards. (The 1997 unit 6 overhaul occurred during the development of the standards for the 1998 unit 4 overhaul.) All operations have a very specific work content, duration (in hours/minutes), crew size, and crew composition.

Project Phases and Timetable

The project had seven phases: top-down development, method-based work standards development, standard validation, customized AutoMOST, MAXIMO-AutoMOST integration, training, and implementation.

The timetable from the top-down development to standard validations was one year. Training and implementation were completed during the LPGP unit 4 overhaul, which required six months.

PROCEDURE AND APPLICATION OF TOOLS

Description of the Main Development Activities

The LPGP unit 4 overhaul job plan database organization consisted of three types of work estimates:

1. Method-based work standards. The method-based work standard database provides a 99 percent confidence interval that the estimated labor-hours are within 2.57 standard deviations.

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[1] AutoMOST is a registered trademark of H. B. Maynard and Company, Inc., Pittsburgh, Pennsylvania.

[2] MAXIMO is a registered trademark of Project Software & Development, Inc. (PSDI), Bedford, Massachusetts.

2. Top-down estimates. The top-down estimate is a detailed method description of the work task. Its estimated labor-hours reflect the craftsperson's experience to perform the work task.
3. Experience estimates. The experience estimate represents specialized work tasks. Its estimated labor-hours reflect the craftsperson's experience to perform the work task. These estimates have minimal impact on the overall work budget.

As the overhaul work orders were completed, all operation steps were reviewed to maintain accuracy. If the work content or work method of the operation step changed during the completion of the work, the associated operation steps in the database were revised to reflect the work modifications. These modifications fine-tuned the database to continue to meet management's goal and expectation: productivity improvement. Operations were not adjusted if the work method change resulted from equipment, material, or tool delays.

Definition and Use of MAXIMO and AutoMOST

In 1994, MAXIMO was installed and a maintenance planning staff was initiated in the hydro and fossil projects. MAXIMO formalized maintenance, capital planning, and recordkeeping for NYPA. It made possible a major improvement in work management at NYPA. MAXIMO was purchased and installed for the benefit of the supervisors and craftspersons.

MAXIMO is a comprehensive, maintenance software system that integrates, among others, work requirements, work standards, material and equipment requirements, scheduling information, and available craft labor. The consultant assisted NYPA personnel to integrate the method-based work standard database into MAXIMO to build job plans. MAXIMO generates a work order with an attached job plan.

AutoMOST is a software tool that uses predetermined logic to develop and integrate job plans in MAXIMO subsequent to the integration of the MAXIMO and AutoMOST programs.

Integration of MAXIMO and AutoMOST

The customized MAXIMO-AutoMOST integration software[3] populated the MAXIMO job plan tables. The integration software transferred all operations, materials, tools, and equipment from AutoMOST to the MAXIMO job plan tables. The integration was developed to generate significant buy-in from all planners. This goal was paramount and was always the focal point throughout the development of the customized MAXIMO-AutoMOST integration software.

The integration software design criteria provided for the following:

- All fields in the MAXIMO job plan tables were populated directly from AutoMOST database by one keystroke command from MAXIMO.
- AutoMOST was activated from the MAXIMO job plan Operations screen.
- Job plans were developed and revised in AutoMOST using predetermined logic that is both logic and data driven.
- All data created by AutoMOST resides in MAXIMO.
- Initially, MAXIMO job plan operations and labor tables were populated.
- Functionality provided a seamless integration to all MAXIMO data tables from AutoMOST.

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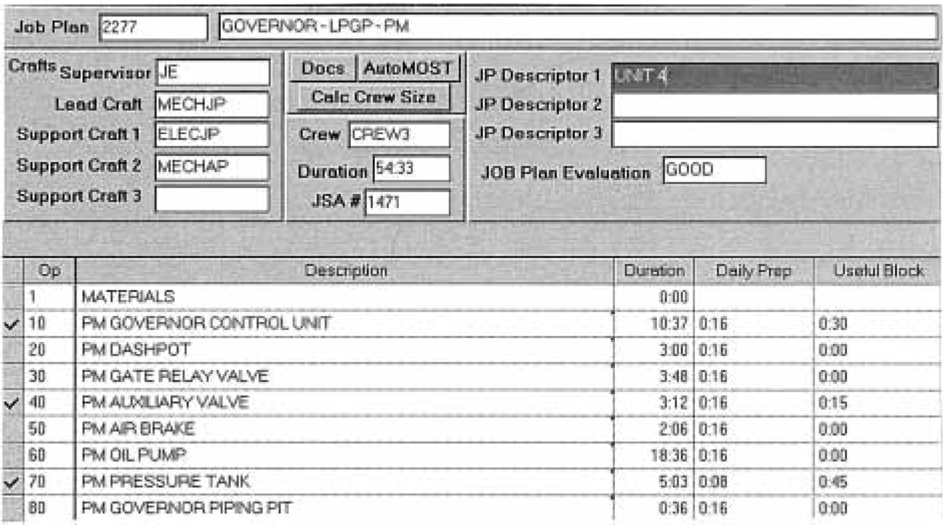
[3] The MAXIMO-AutoMOST integration program has a patent pending.

- Job duration and labor-hour estimates will be adjustable to account for actual jobsite conditions, safety, and travel time to and from the jobsite. This capability is in the MAXIMO work order module with the use of one keystroke.

The MAXIMO-AutoMOST integration software has proven to be very reliable and a significant time-saver when building job plans in MAXIMO for the hydroelectric turbine generator overhaul. Additionally, the NYPA planners have the capability to generate job plans using the method-based work standards database for similar work that is located throughout the Niagara Project. On average, a new MAXIMO job plan with seven operation steps was built in less than 30 minutes. Figure 15.5.1 illustrates a completed job plan.



Job Plan 2277 GOVERNOR - LPGP - PM
Supervisor JE
Lead Craft MECHJP
Support Craft 1 ELECJP
Support Craft 2 MECHAP
Support Craft 3
Crew CREW3
Duration 54:33
JSA # 1471
JP Descriptor 1 UNIT 4
JP Descriptor 2
JP Descriptor 3
JOB Plan Evaluation GOOD

	Op	Description	Duration	Daily Prep	Useful Block
	1	MATERIALS	0:00		
✓	10	PM GOVERNOR CONTROL UNIT	10:37	0:16	0:30
	20	PM DASHPOT	3:00	0:16	0:00
	30	PM GATE RELAY VALVE	3:48	0:16	0:00
✓	40	PM AUXILIARY VALVE	3:12	0:16	0:15
	50	PM AIR BRAKE	2:06	0:16	0:00
	60	PM OIL PUMP	18:36	0:16	0:00
✓	70	PM PRESSURE TANK	5:03	0:08	0:45
	80	PM GOVERNOR PIPING PIT	0:36	0:16	0:00

FIGURE 15.5.1 Job plan.

Building the Job Plan Database

SMEs developed a top-down or work breakdown structure for the turbine generator overhaul. The initial 20,000 labor-hours estimated for the overhaul were segmented into 176 work tasks. A work method description, craft skill requirement, and special work requirements, such as crane or special tools that were needed to perform the work, defined each work task. The labor-hours estimated for each work task were based on the SME's actual, prior experiences to complete the work.

The Pareto's law or the 80/20 rule states that 20 percent of the work tasks account for 80 percent of the total overhaul's estimated labor-hours. Pareto's law governed the selection of 20 percent of the work tasks involving the largest number of labor-hours, within the SMEs' provided work breakdown structure. Method-base work standards were developed for each selected work task. Each standard comprised one or more operations or work steps to complete the selected work task.

Benefits of the Database

With any formal maintenance program, the success of the program is dependent on clear, detailed definition of the work task(s). The job plan database represents the tremendous effort in both manpower and time to ensure clear and detailed definition of the LPGP unit overhaul's work tasks. The job plan database provides viable, accurate, and complete listings of operations, materials, tools, and labor necessary to complete successfully the LPGP unit overhaul's work tasks within the estimated labor-hours.

The database is well suited for ease of revision and improvement. For example, as new technology or new materials become available to revise the work task's method, the task's method will be revised. With each successive improvement, the tasks' estimated labor-hours would be reduced.

The database provides the planners with the capability to develop job plans with the best method. A typical job plan can be developed in less than one hour, while providing the capability to develop accurate schedules with the lowest allocation of labor cost.

IMPLEMENTATION OF NEW JOB PLANS

Application of the Job Plan Database

The time standards reside in MAXIMO job plan tables. Time standards' estimated labor-hours require adjustments before the job plan can be developed and assigned to a work order. All job plan adjustments were completed by MAXIMO-AutoMOST integration software, with minimal planner interaction.

The planner adjusted each standard labor-hour with the appropriate travel time for the craftsperson to complete the job and the preparation time required for the craftsperson to set up tools and equipment, prepare the jobsite, and secure the jobsite for his or her safe performance of the work. The newly revised standard labor-hours were further adjusted with a schedule factor. The schedule factor multiplier was based on the previously observed 1997 LPGP unit 6 overhaul.

The 1.78 schedule factor multiplier provided additional labor-hours to complete the work. Management will require time to remove time delays that have accumulated over the years of operations. Time delays will reduce as management processes are streamlined, which will result in the lowering of the schedule factor multiplier.

The work order duration hours, which are estimated labor-hours divided by crew size, were calculated. Duration hours support effective planning and scheduling of resources among all concurrent work orders. Effective, accurate scheduling and resource coordination will reduce the potential for time delay during the performance of the work.

Upon completion of the standard labor-hour's adjustments, the work standard became a job plan in MAXIMO. The job plan was ready to be attached to a work order.

The Effect of Time Delays

Time delays are the bane of low cost, reliable maintenance. Time delays occur during the performance of the actual work. Time delays hamper the crew's efforts to complete the planned work within the work order's estimated duration. Time delays prevent the improvement of the craftsperson's utilization during the completion of maintenance work. Typical time delays include

- Prints are not available or inaccurate.
- Materials are not available at the jobsite.
- Special job requirements are not defined in the job plan.
- Specialized craft support is not on site when needed.
- Special equipment (e.g., crane) is not available when needed.

- Last minute engineering changes are required.
- Last minute job scope changes are required.

Time delays will reduce as management processes for materials, tools, and equipment are executed efficiently.

The best way for management to determine the root cause for time delay is to observe actual jobs in progress. Unfortunately, time does not permit direct observation. The next best way to determine the root cause for time delay is to talk daily with the supervisor and work crews who are actually performing the work. Time does not always permit this source of information. The only sure way for the planner to analyze time delay is to review reported time delay by the craftsperson on a next-day basis. At this time, the planner can contact the supervisor and work crews who had reported time delay against a specific work order. To reduce the manual analysis, electronic time and control reports were developed to formally provide feedback on work orders in progress. Obviously, any time delay that occurs during the performance of the work should be reported on the craftsperson's time sheet by the craftsperson. Otherwise, the time delay is not known to have occurred and the lack of utilization improvement will continue.

Time Report

An electronic time report system was installed to improve time report accuracy and provide reliable feedback. The system provided the next-day time report for labor-hours spent on a work order the previous day.

When time charges for the overhaul began to exceed work order estimates, it was usually an indication that new work was found or a time delay had occurred. If excessive labor-hours indicated new, unexpected work, the planner would revise the work order or prepare a new work order for the new work. If a time delay had hampered the work crew's efforts to complete the work within the estimated labor-hours, utilization improvement was not expected without planner intervention.

Since utilization improvement is the goal, next-day time report feedback provides the means for a planner to review actual labor-hours reported during the performance of the work. The alternative is reviewing a schedule date or schedule milestone to determine if the work progress is on schedule. Typically, the schedule review occurs after the work is completed. Reported time delays cannot be corrected when the work is completed. To improve work estimating for the ultimate goal of utilization improvement and lower O&M costs, the next-day time report feedback enables the planner to investigate the reported time delay. The planner's analysis will provide immediate and effective resolution to halt additional labor-hour overruns during the progress of the work. This subtle capability enables utilization improvement and lower O&M costs.

Control Report

A control report monitored and evaluated the actual hours expended for all work during the overhaul. The control report identified:

- The total estimated hours for all completed work orders
- Estimated versus actual labor-hours expended to date
- Delay hours that craftspersons had experienced and reported during the performance of their work
- Delay hours reported to date, as a percentage of total department labor-hours
- Overtime hours reported to date

- Overtime labor-hours reported to date, as a percentage of total department labor-hours
- The actual hours divided by the estimated hours were calculated, individually, for electrical, mechanical, and general maintenance departments and all completed work orders

During the LPGP unit 4 overhaul, the planner reviewed the control report for significant labor-hour overruns and underruns. The planner contacted the supervisor and work crew to determine the root cause for time delay reported for work in progress. Their analyses were used to improve the existing material management process and job plans. Figure 15.5.2 illustrates a summary of the control report for completed work orders.

Schedule Factor

Method-based work standards provided the planner with a reference to estimate, plan, schedule, and manage the work. Method-based work standards provided the planner the ability to manage the work with the use of schedule factor or performance factor trends.

The schedule factor is actual labor-hours divided by the work order's estimated labor-hours. Typically, the schedule factor trend is greater than 1, which reflects time delays. Time delays are reduced when the planner and the supervisor manage the schedule factor to approach 1. Success is reducing the actual labor-hours to approach the work order's estimated labor-hours. Figure 15.5.3 illustrates the LPGP unit 4 overhaul schedule factor trend. The sloping line represents a positive, improving trend for the schedule factor.

RESULTS AND FUTURE ACTIONS

Results of the New Job Plan System

Management is looking for dramatic, labor-hour savings, reduced overtime, and improved productivity. A new formal, structured maintenance program, which is based on standards, has the potential to meet their expectations. A significant improvement in past maintenance practices will provide significant labor-hour savings. Since the present state of the electric utility deregulation can be characterized as slow and inconsistent, reasonable expectations are prudent. Management is further challenged with cultures in the electric utilities industry that, in most cases, seem determined to resist change.

Summary of completed work orders

A	B	C	D	E	F	G	H	I	J
Dept.	Work orders complete	Est. hours	Total actual hrs. worked REG + OT	Hrs. dev. (est. – act.)	Reported delay hrs.	Reported delay %	OT hrs.	OT %	Comparison (act./est.)
Mech.	52	6647	6510	137	280	4%	609	9%	.98
Elec.	19	775	861	–86	16	2%	11	1%	1.11
Gen. Maint.	3	64	71	–7	0	0%	11	15%	1.10
Painting	3	97	76	21	0	0%	16	21%	.88
Totals	83	7583	7517	66	295	4%	646	9%	.99

FIGURE 15.5.2 Control report. (*Note:* "Totals" represent *all* work orders, some of which are not included in the four departments in the figure.)

CASE STUDY: DEVELOPMENT OF JOB PLANS IN AN ELECTRIC UTILITY

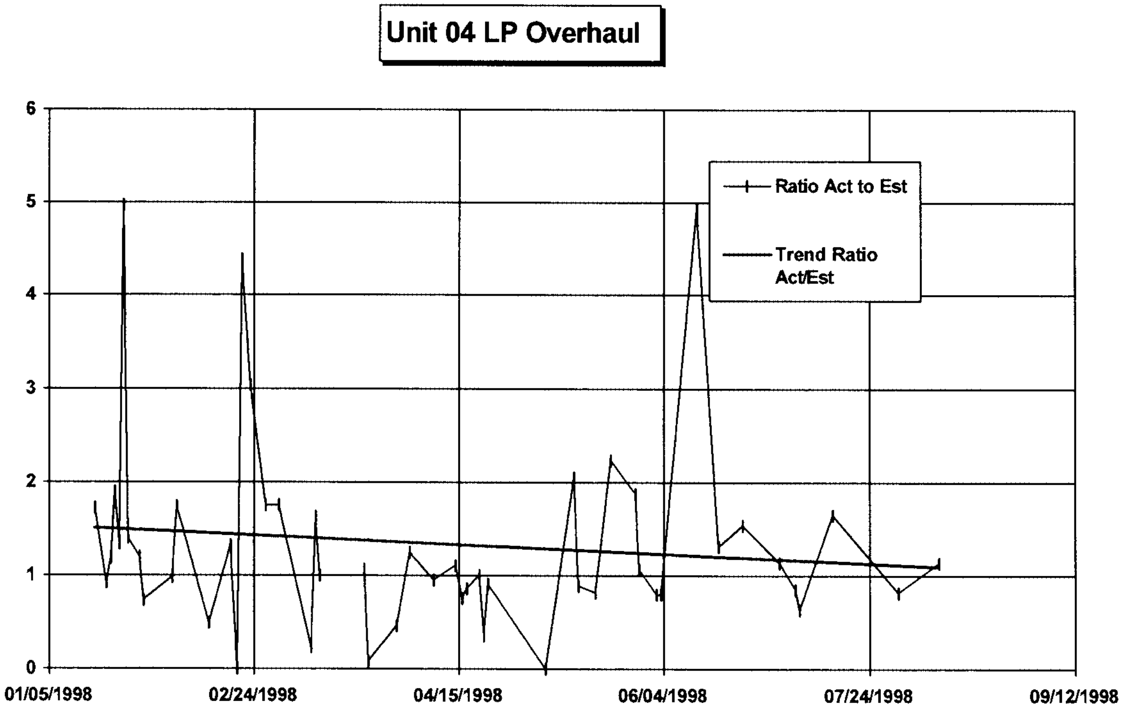


FIGURE 15.5.3 Schedule factor trend.

As NYPA proceeds through the remaining six LPGP unit overhauls, today's expectation for productivity improvement and low-cost maintenance will be achieved. Increased wrench time will provide higher utilization, resulting in higher productivity.

The first LPGP unit 4 challenge for the formal, structured maintenance program was to balance the expectations of the craftsperson with the expectations of management. Over the years, the expectation for overtime became a sense of entitlement. The LPGP unit 4 overhaul attempted to begin in the usual way: planned overtime with the start of the overhaul on a Saturday. After several discussions, the overhaul began on a Monday without overtime. Overtime was a balancing act for the immediate supervisors, while the planner planned and scheduled the work to reduce the need for overtime. During the overhaul, the supervisors provided 1100 hours of overtime, which was a savings of 671 hours of overtime compared to the 1997 LPGP unit 6 overhaul.

As the overhaul continued, parts, materials, and equipment provided significant time delays. During the disassembly of the unit, parts and materials were not time delays because they were not needed. However, equipment failures—the overhead crane in particular—provided time delays repeatedly. Therefore, the supervisor and craftspersons revised the work method during work in progress. Since the estimated labor-hours were based on the best method to perform the work (utilizing the overhead crane), the revised work method resulted in the expenditure of additional labor-hours. Therefore, each revised work method resulted in a higher schedule factor or lower craft productivity. Productivity was lower because the method used by the craft was not the best method or the method requiring the least number of labor-hours to perform the work.

Rehabilitation of the disassembled equipment resulted in instances of parts and materials delays. Since the Niagara Project has four 210 MW, eight 180 MW, and twelve 25 MW hydroelectric turbine generators, similar parts are easily mislabeled or incorrectly ordered from the warehouse.

A report on Wednesdays and Thursdays of each week determined how many parts were issued from the warehouse versus how many parts were issued from the warehouse on Mondays and Tuesdays of the following week. If work orders were fully planned the week before they were issued, materials were drawn from the warehouse on Wednesdays and Thursdays. If planning was incomplete for the work orders, parts were drawn from the warehouse on Mondays and Tuesdays when the job actually began.

In the past, an outside contractor had completed the LPGP unit overhauls. The contractor had planned and executed the work. The outside contractor was replaced with Niagara Project's craftspersons. Therefore, the planning function was also transferred to Niagara Project's planning staff. At the same time, the planning staff was upgrading the Niagara Project's 180 MW hydroelectric turbine generator to 210 MW, which had far greater financial impact because of higher Niagara River flows. (The more water is available, the more MWs can be generated, and the LPGP units are required to pump water into its reservoir to generate MWs during peak demand). On a simple financial basis, the 180 MW unit upgrade was significantly more valuable than the 20 MW LPGP unit overhaul. The priority was the 180 MW unit upgrades. In most instances, parts for the LPGP unit 4 overhaul were drawn from the warehouse on Monday or as the work progressed.

A planned, concerted effort on the part of the Niagara staff achieved savings of 423 labor-hours associated with targeted work method improvements. Work method improvements were planned and executed for rehabilitation of the generator rotor and the replacement of the turbine stationary wearing ring.

The generator rotor required the replacement of the amortisseur windings shorting bar. The amortisseur windings are on each pole face of the generator rotor. Each pole has a top and bottom amortisseur winding shorting bar. On previous overhauls, the contractor used a flame torch to soften the silver solder, which attached the shorting bars to amortisseur winding. The torch was time-consuming and dangerous. An induction heater was designed by Niagara staff and implemented successfully on the LPGP unit 4 generator rotor. The craftspersons and planner pursued the induction-heating concept. Their work saved 200 labor-hours compared to the previous LPGP unit 6 overhaul for the replacement of the amortisseur windings shorting bars. The work order schedule factor was 1.54, which was a productivity improvement of 15.6 percent from LPGP unit 6.

The turbine stationary wearing ring replacement began one year before the LPGP unit 4 overhaul scheduled start date. The quality control inspector telephoned the Niagara Project from the wearing ring's manufacturing floor in Italy. Since the wearing ring was replaced in the 180 MW hydroelectric turbine generator upgrade in one piece, the inspector asked why the manufacturer cut the ring into halves for the LPGP unit 4 overhaul? Further, past experiences during similar NYPA turbine wearing ring replacements highlighted the 1989 labor-hours that the contractor spent on the 1997 LPGP unit 6 turbine stationary wearing ring.

The LPGP unit 4 overhaul supervisor detailed a new shrink fit work methodology to install the wearing ring in one piece. A shrink fit was designed for 80 thousandths of an inch, with engineering approval. The supervisor designed the placement of oversized boxes to submerge the entire ring in dry ice. The ring was supported by a spoked wheel configuration (similar to a bicycle tire where the ring replaced the rubber tire). After 30 hours, the wearing ring shrank 200 thousandths of an inch. The wearing ring was lifted from the dry ice and lowered into position with minimal force. The one-piece wearing ring was installed successfully with the resulting savings of 223 labor-hours. The schedule factor for the turbine stationary wearing ring work order was 1.58, a 12.7 percent improvement in productivity. During the performance of their work, the craftspersons reported 131 hours of time delay.

The LPGP unit 6 overhaul completed in 1997 had a schedule factor of 1.78. Therefore, productivity for the 1997 LPGP unit 6 overhaul was 56 percent. The initial implementation of the new formal, structured maintenance program on the 1998 LPGP unit 4 overhaul performed at 57 percent productivity or a schedule factor of 1.76. The completion of unit 7, the second unit

CASE STUDY: DEVELOPMENT OF JOB PLANS IN AN ELECTRIC UTILITY

overhauled after the initial implementation of the structured maintenance program, provided a productivity improvement from 57 percent to 71 percent, which represents an additional reduction of 2860 labor hours. The schedule factor is 1.41.

Required Actions to Maintain and Enhance the Work Management Process

The planning process provides the work crew the tools to increase the amount of work performed at the jobsite. To effectively plan scheduled work, the organization works closely together so that scheduled work will occur when the necessary materials, tools, and equipment are ready for the craftsperson to start work. Proactive efforts to avoid delays during maintenance work requires continuous management reinforcement. While no one can eliminate all delays, strong management efforts to reduce time delays provides an immediate improvement in utilization.

Improved material supply is under management review. The development and refinement of the material management processes will improve material supply to a level acceptable to the craftsperson. One area of improvement that will be expanded is kitting and delivery of parts and material to the craftsperson at the jobsite. This single improvement will increase the craftsperson's presence at the jobsite an estimated 10 percent, based on a recent work sampling measurement. In the past, the craftsperson left the jobsite and withdrew parts from the warehouse. Typically, the craftsperson's travel time is approximately 20 minutes per round trip, plus the time to find and withdraw the correct parts. Therefore, the total unproductive time to obtain parts after the job is placed in progress is at least 45 minutes for each craftsperson in need of parts. With consideration of the number of available craftspersons, substantial utilization gains will be achieved on implementation of an improved materials management process.

Management processes, in a traditional view, provide a common set of processes that, when competently carried out, contribute to organizational effectiveness and efficiency. The basic processes are planning, organizing, leading, and controlling. Method-based work standards are one component of the work management process. The standards provide an objective time estimate to complete specific work. Management processes provide the continuous handshakes to execute and complete the work within the time estimate and at the lowest costs. To approach a schedule factor of 1, a formal structured maintenance program together with objective time estimates and streamlined management processes will provide continuous O&M productivity improvements.

CONCLUSION

Deregulation has forced managers to reconsider their cost controls. Typically, NYPA manages the schedule to control cost. The schedule provides decision points. The decisions determine cost.

However, to further gain O&M cost reductions, managing the schedule to control costs is too remote from the resources or cost centers. Resources need direct management. When resources are carefully managed, the work is planned, controlled, and executed as the scarce resources are available. The resource level is precisely where the O&M dollars are actually spent: the craftsperson's wage, the purchase of materials, and the purchase of equipment. These costs drive the cost of doing business. In a newly deregulated business, management recognizes the gateway to productivity improvement, in a culture that often seems determined to resist change, is in the first-line supervisor's office. The tools available to the supervisor govern the productivity of the craftsperson. To narrow the chasm between expectations and experiences, resources are effectively and efficiently managed.

For the first time, NYPA managed an overhaul at the resource level with the use of the new structured work management process. Standards provided the target labor-hours for the work. The schedule factor was applied at the resource level with control reports as a formal feedback to manage performance.

Since the 1931 Power Authority Act, the management methodology for the LPGP overhaul had never changed so radically. There were difficult adjustments to be managed. Handshakes were visualized and the overhaul team solidified. Debate both for and against standards will continue. Standards drove a new way to perform work. Standards allowed NYPA to recognize what was always known—that the management processes, the warehouse, the tool cribs, and the accounting and administration exist for one reason: to support the craftsperson and his or her supervisor. Method-based work standards provided NYPA with an outstanding challenge for their introduction to the LPGP unit 4 overhaul.

Once management processes are well maintained and streamlined, managing the schedule factor will approach 1 and O&M will be completed at low cost every time.

BIOGRAPHY

Franklin P. Frisina, P.E., a senior performance engineer for the New York Power Authority (NYPA), has over 27 years experience in operations and maintenance of hydroelectric and fossil generating facilities, and engineered and designed nuclear and hydroelectric generating facilities. He graduated from State University of New York at Buffalo with a B.S. in electrical engineering, from Iona College in New Rochelle, New York, with an M.B.A. in finance, and from Polytechnic University, Brooklyn, New York, with an M.S. in electrical engineering. Frisina has produced, written, and directed two award-winning, animated tutorial videos on Niagara Project's unit upgrade program and the NYPA Energy Control Center. The Energy Control Center schedules, dispatches, and controls all NYPA-generated electricity throughout the State of New York. Frisina has two patents pending for software interfaces to MAXIMO to improve management processes.

CHAPTER 15.6

CASE STUDY: LABOR CONTROLS FOR A BANK

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Today more and more jobs are generated in the service sector, where simultaneously less effort has been focused on establishing conventional labor control systems. It is therefore becoming more and more important to establish such control systems adapted to meeting the requirements regarding efficiency and competitiveness in the service industry. In addition to being a sound management tool, a good labor control system is essential in the effort to improve productivity and reduce costs. This chapter will discuss the implementation of engineered labor standards and labor control reports at a large U.S. bank. The project steps and the results from the project are part of this case study.

BACKGROUND AND SITUATION ANALYSIS

Competitive pressures resulting from numerous mergers in the banking industry are causing banks to rethink how they do business and how they can improve their operations. H. B. Maynard and Company was approached by a large U.S. bank to discuss the challenges they were facing due to the increased competitive pressures. During discussions with the bank, it was obvious that managers and supervisors were under increasing pressure to reduce staff at the same time that the workload and customer requirements were increasing. The initial focus was placed on the Returned Check processing operations. The majority of the clerk-hours in this department were spent on highly repetitive operations, including reading information on checks and entering the information at a computer keyboard, sorting checks, and summing check amounts using an adding machine. Some of the operations were more variable and less repetitive, especially those performed by the work leaders.

Several key findings related to the bank's labor control system were:

- Outdated work quotas
- Quotas did not reflect the various methods at different operation centers
- Inadequate performance measurement

- No precise way of determining staffing requirements
- No formal way to identify or quantify improvement opportunities

The quotas used for staffing were outdated and had no backup; the supervisors had no confidence in the existing work quotas. These quotas did not reflect the methods and equipment used by the bank, and increased customer requirements, and other methods changes were not reflected. The other operations centers in the four cities that were acquired through mergers used different equipment and work practices, yet they were measured against the same quotas. Performance measurements used for employee reviews were based on these same outdated quotas and did not reflect the whole day's work.

There was no staffing model to determine the number of employees needed at each site. Productivity was not measured, and the bank had no way of identifying all the various problems encountered during the normal course of a day. Management could not understand why it was taking more time to process the same number of checks, and the lower-level managers and supervisors could not understand why their requests for additional staffing to satisfy increased customer requirements were not approved.

The bank expressed an interest in having accurate labor standards in the Returns Department for accurate costing, staffing decisions, performance measurement, and a way to determine best methods. They also wanted to quantify what special instructions for customers were actually costing the bank.

OBJECTIVES AND SCOPE

The Returns Department consisted of two areas: (1) incoming and (2) outgoing returns. There were three operation centers that were included in a pilot project to improve the bank's labor control system.

The project had the following objectives:

1. Develop engineered time standards for the services provided by the Returned Checks Department. The standards would be created by using a combination of (1) a MOST® predetermined time measurement system for the highly repetitive tasks, and (2) time study for the less repetitive and more variable tasks.
2. Develop a PC spreadsheet–based labor report to calculate labor performance, delay, and overall productivity levels for the Returns Department.
3. Develop a staffing model that the bank could use to determine staffing levels based on the major work volume indicators.
4. Recommend methods improvement suggestions at the three sites.

ORGANIZATION OF PROJECT

The project was organized into three phases, one for each of the three selected sites. The team consisted of the best practices coordinator, a bank operations specialist very knowledgeable in the Returns Department, the supervisors for each of the three sites, and the consultant. The work leaders as well as the employees were involved throughout the project.

PROCEDURE AND APPLICATION OF TOOLS

The pilot project included the following specific project steps.

Standard Time Development

The bank's Returns Department supervisors and best practices team members provided a list of job tasks for the personnel in the Returns Departments. The bank operations specialist and the consultant documented the methods used to perform each task. The MOST predetermined time system was used to determine the standard time for repetitive tasks that could be performed consistently with little method variation. Time study, including performance rating, was used for less repetitive, variable tasks. Most of the tasks were filmed for close analysis and discussions of proper method.

Figure 15.6.1 shows an example task analyzed at the bank. Each task was made up of several steps of basic data, with the appropriate frequency of occurrence for each step. If a step occurred simultaneously with another step, the frequency was shown as "int," representing *internal.*

The basic standard data shown in Fig. 15.6.2 are the common repetitive elements of work that make up various tasks performed by the clerks. This data was developed using the MOST predetermined time system. The approach of using standard data in combination to represent the various tasks is faster and more consistent than directly measuring the time for each task.

Staffing Model

A PC spreadsheet was developed to serve as the staffing model. The staffing model, Fig. 15.6.3, is divided into two major parts. The header of the staffing model contains the drivers or major volume indicators. The average number of incoming and outgoing checks serves as the drivers for this staffing model. The frequency of most tasks performed in the department can be estimated as a ratio of the number of occurrences of the drivers. Therefore, as the number of checks increase or decrease, the time to perform all of the occurrences of each task will increase or decrease accordingly. The driver for the staffing model is the incoming checks represented by the letter "A" in the staffing model. By inputting the anticipated number of checks, the bank is able to forecast the number of standard hours of labor needed to accomplish the forecasted workload. This is especially useful in the banking industry, since the volume of checks is predictable (but does vary based on the day of the week and time of the year). The staffing model identifies when staffing changes are justified. Simulations are also run with this staffing model to gauge the effect of decisions to potentially change a task or change the frequency of a task.

Match checks to notices		Hrs 0.00119	
Data_ID	Description	Freq	TMU
7	Read dollar value on check and notice	2	21
8	Read each additional word, number, etc.	8	26
7	Read customer name on check and notice	2	21
8	Read each additional word, number, etc.	2	7
36	Turn check over to other side	0.1	2
7	Read account number 2 places	0.2	2
36	Place notice to check	1	Int
51	Place notice/check to stapler	1	13
38	Process time for stapler	1	3
17	Remove check from check carrier	0.1	8
50	Aside notice/check	1	16

FIGURE 15.6.1 Sample task.

ID	Description	Per	TMU
1	Transport trays to or from Processing	trip	5644
2	Write 2 digits	digit	50
3	Write 3–4 digits or 1 word	digit	80
4	Write 5–6 digits	digit	120
5	Write 7–9 digits or 2 words	digit	180
6	Write 10–13 digits or 3 words	digit	260
7	Read first word, number, phrase, etc.	digit	10.6
8	Read each additional word, number, etc.	digit	3.3
9	Transport item to or from within 20 steps	trip	860
10	Stamp item with hand stamp	action	40
11	Cut item with scissors	use	110
12	Place tape	pcs	90
13	Remove rubberband	occ	90
14	Remove plastic bag	occ	160
15	Remove paperclip	occ	70
16	Remove staple	occ	115
17	Remove check from check carrier	occ	80
18	Remove tape from adding machine	occ	50
35	Sort through checks	check	12
36	Turn check over (to aside or read)	check	18
37	Process time up to .1 sec or 1.7 tmu	occ	1
38	Process time up to .2 sec or 4.2 tmu	occ	3
39	Process time up to .3 sec or 7.7 tmu	occ	6
40	Process time up to .5 sec or 12.6 tmu	occ	10
41	Process time up to 1.0 sec or 27.7 tmu	occ	24
42	Go to Fed bank and back	occ	35000
43	Assemble or disassemble bundle w/rubberband and cash letter	bundle	208
44	Assemble or disassemble bundle w/paperclip and add. mach. tape	bundle	111
45	Open envelopes for stuffing	envelope	9
46	Pickup object within 4 inches	occ	15
47	Aside object within 8 inches	occ	12
48	Move object up to 14 inches away	occ	32
49	Regrasp object	occ	6
50	Aside object within 14 inches	occ	16
51	Place but retain control of object	occ	13
52	Place object within reach	occ	60
53	Aside object within reach	occ	20
54	Place item in envelope	occ	44

FIGURE 15.6.2 Basic data.

The body of the staffing model contains the tasks and frequency information developed during the study. Each column in the staffing model has been assigned a letter for description purposes.

a The identifier for the task. “Dx” designations are tasks developed with MOST, and “Mx” designations are tasks developed with time study.

b The task description.

c The standard time it takes to accomplish the task.

d The ratio that the task occurs in relation to the driver.

Return check staffing model

Drivers	Description	Volume	Drivers	Description	Volume
A	Incoming checks	3000	E		
B			F		
C			G		
D	Outgoing checks	5500	H		

a	b	c	d	e	f	g	h
Task	Description	Task (Hrs)	Partial Freq.	Frequency Formula	Frequency Per Day	Hours	%
D1	Pickup checks from Check Processing	0.05644		2	2.0	0.11	2%
M7	Separate checks/notices/redeposits	0.11667		2	2.0	0.23	4%
D112	Sort rejects into amount order	0.00120	5%	A	150.0	0.18	3%
D104	Prep check for matching	0.00018	7%	A	210.0	0.04	1%
D105	Pull checks from carriers	0.00080	7%	A	210.0	0.17	3%
D22	Match small notice to check	0.00119	32%	A	960.0	1.15	22%
D23	Match long notice or cashletter to checks	0.00060	32%	A	960.0	0.58	11%
D24	Look for rejected check	0.00878	4%	A	120.0	1.05	20%
D25	Open envelopes	0.00017	34%	A	1020.0	0.17	3%
D32	Stuff envelopes	0.00064	34%	A	1020.0	0.65	12%
D107	Stamp redeposits	0.00040	36%	A	1080.0	0.43	8%
M15	Special handling for various accounts	0.25000		1	1.0	0.25	5%
M5	Stamp/validate remaining rejects	0.08333		2	2.0	0.17	3%
D1	Deliver/distribute work to other departments	0.05644		2	2.0	0.11	2%
D20	Deliver/distribute work in area	0.00860		2	2.0	0.02	0%
					0.0		
					0.0		
					0.0		
					Total Hours		5.31
					Allowance		1.26
					Standard hrs		6.67
					FTE @ 100%		0.9
					Target Prod.		80.0%
					FTE @ Target		1.1

FIGURE 15.6.3 Staffing model.

e Represents the driver for the task or a number representing the times per day that the driver occurs.

f The product of columns “d” and “e”; represents the total times per day that the task occurs.

g The total time that a task will take each day; calculated by multiplying columns “c” and “f.”

h The percent of the workday that the given task will take. Column “h” is calculated by dividing column “g” by the “Total Hours” shown at the bottom of the body of the staffing model.

Allowances are then added to the total hours to obtain the standard hours. The next line is the staffing requirement at a 100 percent productive level. The target productivity represents the acceptable productivity level as determined during the project. The last line of the staffing model shows the staffing requirement as per the target productivity level. In the example, the staffing requirement increased from 0.9 full-time equivalent (FTE) staff at 100 percent productivity to 1.1 FTEs at the target productivity level of 80 percent.

As mentioned earlier, as the volume for the drivers are altered, the staffing level will change to reflect the new volume.

Labor Reporting

A PC spreadsheet labor control report was developed to report key performance characteristics including performance, delay, and overall productivity. The labor report uses the staffing model to determine the appropriate number of earned hours based on actual checks processed. The input needed is actual hours and actual processing numbers. Figure 15.6.4 shows an example control report from one of the sites.

The header of the control report uses the same drivers as the header of the staffing model. The difference is the actual volume of checks processed and is entered in the control report header to gauge efficiency where the staffing model uses a predictive volume of checks for future staffing determinations.

The body of the control report details some key information along with the source of the information. The basic inputs to the body of the control reports are the earned hours from the staffing model, along with time card information. The rest of the information is calculated based on the inputs.

The returns time and production control report is used by bank management to pinpoint performance and delay problems and implement procedures to control the causes of these labor variances.

The timecard shown in Fig. 15.6.5 was designed to collect key information about the workday from each clerk. The key information from the timecard is the total hours worked, delay or nonstandard code, along with the associated hours. The delay codes were developed based on typical delays that bank personnel experience.

Returns Time and Production Control Report

Drivers	Description	Volume	Drivers	Description	Volume
A	Incoming checks	3000	E		
B			F		
C			G		
D	Outgoing checks	5500	H		

	Description	Value	Source of Information
A	Earned hours @ 100% of model	46.0	Staffing model
B	FTE @ 100% of model	5.5	Staffing model
C	Scheduling factor	80%	History/management decision
D	Target hours w/ scheduling factor	57.5	A / C
E	Target FTE w/ scheduling factor	6.9	B / C
F	Actual hours on standard	46	Timecard
G	Non-standard hours	1	Timecard
H	Delay hours	12	Timecard
I	Total	59	Timecard F + G + H
J	Performance	100%	A / F (Earned hours / Actual hours on standard)
K	Delay	20%	H / I (Actual delay hours / Total actual hours)
L	Productivity	79%	(A + (.85 * G * J))/I
M	Percent of target	97%	D / I (Target hours / Total actual hours)

FIGURE 15.6.4 Labor control report.

Time Card

Name Nancy Kuchar Date April 1, 1997

Dept 100 Total hours worked 8 Start time 08:00 Stop time 04:45

Delay/Nonstandard/Transfer reporting

Time	Duration	Code	Remark
09:00	:15	220	Wait on work from FED
02:00	:30	250	Team training

Supervisor Marguerite Wilson

Delay/Nonstandard/Transfer reporting (Cont.)

Time	Duration	Code	Remark

Delay Codes
210 Late work—internal
220 Late work—external
230 No work
240 Meeting
250 Training
260 System problem
290 Misc

Non-std Codes
100

FIGURE 15.6.5 Time card.

A spreadsheet was developed to summarize the timecard information and feed the control report.

Detailed procedures for labor control were developed, including the necessary steps in filling out a time card, production and distribution of the control report, and analysis of the report.

Site Comparisons

Comparisons between methods at the three sites were made to determine which methods were most efficient. A “best practices” committee was charged with implementing the best methods at all of the sites.

Work Management Manual

During the project, work management manuals were developed for each of the three sites to document the conditions reflected in the standard data. The manuals provide a reference for auditing the standards for changes in the methods and procedures used in the Returns Department. Below are the major sections contained in the work management manuals.

- Scope (describes the areas and operations covered)
- Standard Practices (defines the clerks’ responsibilities for the workplace, work, equipment, setups, work assignments, reporting, safety, etc. that are included in the time standards)
- Facilities and Equipment (documents all equipment used)
- Workplace Layout (shows the layout of the area covered by the manual)
- Process Data (documents the process times used in the time standards and how they were derived)
- Manual Methods (contains the standard operating procedures for performing the work)

- Standard Time Calculation (documents how the standards were set)
- Standard Data Backup (contains all the MOST data used during the establishment of the time standards)
- Allowances (documents the allowances applied to the time standards)
- Standards Maintenance (describes when a standard should be revised and who is responsible for revising the standards)

IMPLEMENTATION OF CHANGES AND IMPROVEMENTS

Throughout the development of the time standards, a number of methods improvement ideas were identified which would reduce cost and improve productivity. Specific recommendations based on these ideas were as follows:

- Implement high-speed data entry (machine read information) where possible. Potential savings are high compared to employing manually entered data and justify the additional equipment where needed.
- Investigate the use of multipocket machines (most efficient of high-speed data entry machines observed) for processing outgoing checks at all sites. Potential savings are high compared to the other methods used by the remaining sites. Other high-speed data entry machines at one site should be modified so that the back of the checks can be seen. This modification would reduce the manual check handling currently required by this type of machine.
- Reduce keystrokes where practical. Three areas identified for reducing keystrokes are:
    1. Use the most common entry in some fields as the default value in the software to reduce keystrokes. If the default value is the right answer, there is no need to require keystrokes; simply move on to the next field.
    2. Link the data entry screens to other databases where possible to reduce keystrokes. Some of the required fields for data entry can be filled in automatically by information found in other databases at the bank.
    3. Place all commonly needed fields together on one screen to reduce the tabbing needed to get to the next field or to the next screen.
- Reduce manual (i.e., longhand) writing. Manual writing is time consuming compared to typing. Manual writing is also harder for the next operator to interpret. The use of adding machine tapes and software modifications to permit keying will reduce cost and also reduce the confusion of reading handwritten information.
- Provide necessary tools and supplies at each workstation. It was observed on several occasions at two of the sites that a clerk had to leave his or her work station to obtain a stapler or staple remover and then return it when finished. Necessary clerical tools at each workstation would eliminate these types of delays.

General recommendations based on observation and our experience in labor control are listed as follows:

- Measure and implement labor controls throughout all bank operations. It is our experience that productivity increases when attention is given to time reporting and analysis of variances from standard. Special attention should be given to reasons for delays and how to reduce these delays.
- Cross-train clerks. Observations at one site made it apparent that cross-trained clerks can move from one task to another with little or no effort. This training effort is largely the reason why this site experienced fewer delays than the other two sites.

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- Maintain and audit the staffing models. The need for accurate staffing models is obvious when considering the lack of confidence in the previous bank staffing reports.
- Generally people will try harder to make a standard if they understand and believe it is accurate. Accurate staffing models will provide for better decision making when considering potential changes in work methods. The staffing model should be audited and maintained by the bank's centralized operations services group.
- Best-practices meetings should be held periodically at the various sites. This will improve the understanding by all best-practice members on how each site operates. These meetings should also make the implementation of the best methods quicker and with more confidence.
- Team meetings should be initiated at the start of the shift. The feasibility of a team meeting at the start of the shift should be considered for all sites. Experience with other companies and observations at one bank operation center show that a short meeting at the start of the shift improves long-term productivity. Feedback from the previous day and other issues can be communicated and problems resolved in this meeting.

RESULTS AND FUTURE ACTIONS

Although there was some resistance to change by some bank personnel, others saw the benefits from improving labor controls, and pushed on with the implementation of the staffing model and the reporting system. Within the first six months following the end of the project, the bank improved productivity in the Returned Checks Department by an average of 14 percent. The improvement in productivity was mainly due to their analysis of reported delays and elimination of the root causes of those delays.

Software modifications as well as other methods improvements were also implemented, which resulted in lowering the bank's cost to process returned checks.

As the benefits of reducing delays and implementing methods improvements became apparent, the bank decided to expand the project. Several bank operations specialists were trained in the appropriate techniques and are expanding the project into the remaining back office operations in the bank. Industrial engineering principles were shown to have great value in the banking industry.

BIOGRAPHIES

Joseph May is a business development manager with H. B. Maynard and Company, Inc., based in Pittsburgh, Pennsylvania. May has assisted Maynard clients for 20 years, most recently by designing improvement programs and then managing Maynard staff members in providing assistance with those programs. May has a B.S. in industrial engineering from Purdue University in West Lafayette, Indiana.

Kevin Hilliard is a senior consultant with H. B. Maynard and Company, Inc. His consulting career spans 14 years and he presently consults with clients on productivity issues and practices. Prior to consulting, Hilliard held positions in industry as an industrial engineer and plant engineer. He holds a B.S. in industrial engineering from Geneva College, located near Pittsburgh, Pennsylvania. Hilliard is a senior member of the Institute of Industrial Engineers (IIE).

SECTION 16

MAINTENANCE MANAGEMENT

Source: MAYNARD'S INDUSTRIAL ENGINEERING HANDBOOK

CHAPTER 16.1

COMPUTER-AIDED MAINTENANCE PLANNING, SCHEDULING, AND CONTROL

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Maintenance management is a very information-intensive process. The computer is an ideal platform for managing the large amounts of information and separate communications that must occur to get the work done. A *computer-aided maintenance planning, scheduling, and control system,* also referred to as a *computerized maintenance management system* (CMMS), is the application software for tasks such as initiating work requests, and planning and scheduling work orders from the approved requests. Other tasks are planning and scheduling repetitive preventive maintenance jobs, time reporting, maintaining equipment specification and history, and automatic generation of performance reports and trend charts. Some CMMS programs also have integrated purchasing and material stores applications and electronic data interfaces with vendors. This chapter describes for the industrial engineer how to develop a computer-aided system for organizing, planning, scheduling, measuring, and controlling maintenance. The system described also provides a framework for assessing, evaluating, and improving an existing CMMS program. It is applicable in either a union or nonunion environment, and it gives industrial engineers and engineering managers the critical building blocks for a dynamic process, performance goals, and continuous improvement. Based on a sound maintenance policy and tested maintenance principles, it announces a mission and evokes integrated participation by higher management, support functions, and the maintenance staff.

INTRODUCTION

The hundreds of commercial CMMSs plus many more in-house systems emphasize management's realization of the importance of real-time information access in maintenance. These systems employ mainframe computers, minicomputers, and networked PCs for work order control, preventive maintenance (PM), equipment history, and material stores control.

Wide Scope of Computer Uses in Maintenance Management

Laser bar code scanners are expanding from production and warehousing to maintenance material stores. Data management systems store information about equipment operation, maintenance methods, and parts online for instant retrieval from the field or shop. Heads-up displays link workers with repair procedures for on-the-job training, which results in faster, high-quality repairs. Laptop computers with digital radio transmitters are connected to the client/server network so the planner can transfer information from the field into the computer, look up spare parts stock status, and generate work orders remotely. Internet service providers (ISPs) are an important resource for expanding database capacity and 24-hour vendor contact. With the addition of PC-programmable controllers, computers change setups, diagnose machine variations, automatically issue work orders, adjust tolerances automatically to maintain acceptable limits, and call for human intervention when a problem is beyond the machine's capability. However, labor-free maintenance is even further away than labor-free production. In the following sections of this chapter, the industrial engineer will find a description of characteristics of good user interfaces; properties and benefits of a CMMS; and how to integrate the CMMS with sound principles, management policy, and shop floor controls.

Basic Maintenance Management Principles

Six proven principles ensure success when applied to organizing the maintenance function. They are the principles of optimum productivity, measurement and control, customer service, optimum crew size, timeliness, and activity responsibility. These principles are defined in the following paragraphs, and computer aids to implementation are described.

Optimum Productivity Principle. Optimum productivity occurs when each person in the maintenance crew has a definite job to do, in a definite way, and a definite time. The computer facilitates implementation of this principle when it is used to plan, schedule, and assign each work order, track materials, and backlog.

Measurement/Control Principle. Measurement of an activity is essential before effective control can exist. The computer stores work measurement data and provides a rapid, accurate method for applying standard times to each work order.

Customer-Service Relationship Principle. Operations personnel are the customers. They pay the bill. Maintenance provides the required service. Operations decides what is needed and when. Maintenance decides how to perform the service and supports operations in deciding when (priority) the work is to be done. Computer databases include repair methods, work order priorities, status, and stores activity strengthening this relationship.

Optimum Crew Size Principle. The optimum crew size is the smallest number of workers who can perform a job using a good, representative method in a safe way. A computerized standard crew size application defaults to one, the crew size for most maintenance jobs. Larger crews are the exception.

Timeliness Principle. Computerized schedule control points are set so that potential completion delays are detected in time to take corrective action.

Activity Responsibility Principle. Efficient work order control requires that management assign definite responsibility for each activity in the life of a work order. Computerized control of activity starts when the requester defines the work and ends when the follow-up audit of the completed job by the supervisor is documented to ensure quality and completeness and to provide an audit trail. (See Fig. 16.1.1.)

Activity responsibility begins with a clear, well-articulated mission statement and a policy for mission attainment, which includes tangible measures and goals documented in the computerized standard practices manual for easy retrieval and updating. (See Chap. 16.8.)

KEY:
R = RESPONSIBLE
C = COORDINATES
A = ASSISTS
NOTE: FOR EACH WORK ORDER, ONLY ONE
"R" APPLIES TO EACH ACTIVITY

WORK ORDER ACTIVITY RESPONSIBILITY CHART

				PLANT ENGINEERING DEPARTMENT				
ACTIVITY DESCRIPTION	PRODUCTION SUPERVIS'R	ENGINEER OR ADMIN.	PRODUCTION COORD	PLANT ENGINEER	MATERIAL STORES	MAINT. SUPERVISOR	PLANNER	MAINT. TECH.
1. DEFINE WORK REQUEST CONTENT	R	R	R	R		R	A	
2. PREPARE WORK REQUEST	R	R	R	R		R		
3. INITIATE ENGINEERING WORK ORDER		R		R				
4. APPROVE WORK REQUEST				R				
5. SET PRIORITY & COMPLETION DATE	R	R	R	R		C	A	
6. DELIVER WORK REQUEST	R	R	R	R	A	R		
7. FIELD CHECK. DETERMINE WORK CONTENT	A	A		A		C	R	
8. DECIDE MATERIAL, TOOLS, EQUIPMENT & LABOR		C		C		C	R	
9. CHECK MATERIAL, TOOLS, EQUIPMENT AVAILABILITY							R	
10. FIND MATERIAL, TOOLS & EQUIPMENT					R		A	
11. REQUISITION PURCHASED MATERIAL, TOOLS					A	C	R	
12. STAGE MAT'L, TOOLS, EQUIP. FOR DELIVERY					R		A	
13. DELIVER MAT'L, TOOLS, EQUIP. TO JOB SITE					R		A	R
14. MAKE JOB SITE AVAILABLE	R	R		C		C		
15. PREPARE & ASSIGN WEEKLY WORK SCHEDULE	A	A		R		C	A	
16. ASSIGN WORK ORDERS TO CREW BY WORK TYPE				R				
17. SEQUENCE MULTI-CRAFT JOBS						C	R	
18. COORDINATE MULTI-SHIFT JOBS						R		
19. PROVIDE PERMITS/ADMISSION TO WORK AREAS						R		
20. ASSIGN INDIVIDUALS TO WORK ORDERS DAILY						R	A	
21. ASSIGN INDIVIUDALS TO PM TASKS						R		
22. PREPARE SUPERVISOR'S DAILY WORK SCHEDULE					A	R	A	R
23. PREPARE INDIVDUALS' DAILY WORK SCHEDULE						R	A	
24. VERIFY JOB STATUS, QUALITY & COMPLETENESS		A		R	A	R	A	
25. DO ASSIGNED JOBS, REPORT TIME, DELAYS ADDITIONAL WORK DONE OR NEEDED, EACH JOB								R
26. RECORD EQUIPMENT ID'S/SPECIFICATIONS IN MP2							R	
27. DESIGN PM TASKS AND FREQUENCY				C			R	
28. APPLY STANDARD HOURS TO WORK ORDERS & ADJUST FOR CHANGES			C				R	
29. REPORT TIME, ADDED WORK & DELAYS DAILY								R
30. APPROVE TIME & DELAY REPORTING						R		
31. ENTER TIME & DELAYS & CLOSE WORK ORDERS					R			
32. PREPARE/DISTRIBUTE WEEKLY CONTROL REPORT							R	
33. ANALYZE WEEKLY CONTROL REPORTS			R	R		R	A	
34. ANALYZE EQUIPMENT HISTORY		A		R	A	A	A	
35. INITIATE PM CORRECTIVE ACTION				C		R	A	
36. AUDIT EMS DATA & APPLICATION			R	C			A	
37. AUDIT SYSTEMS & PROCEDURES			R	C			A	
38. DEVELOP OR REVISE EMS DATA			C	A			R	
39. APPROVE INTERNAL MAINTENANCE WO'S				R				
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FIGURE 16.1.1 Activity responsibility chart. (*Reprinted with permission from Productivity Network, Inc.*)

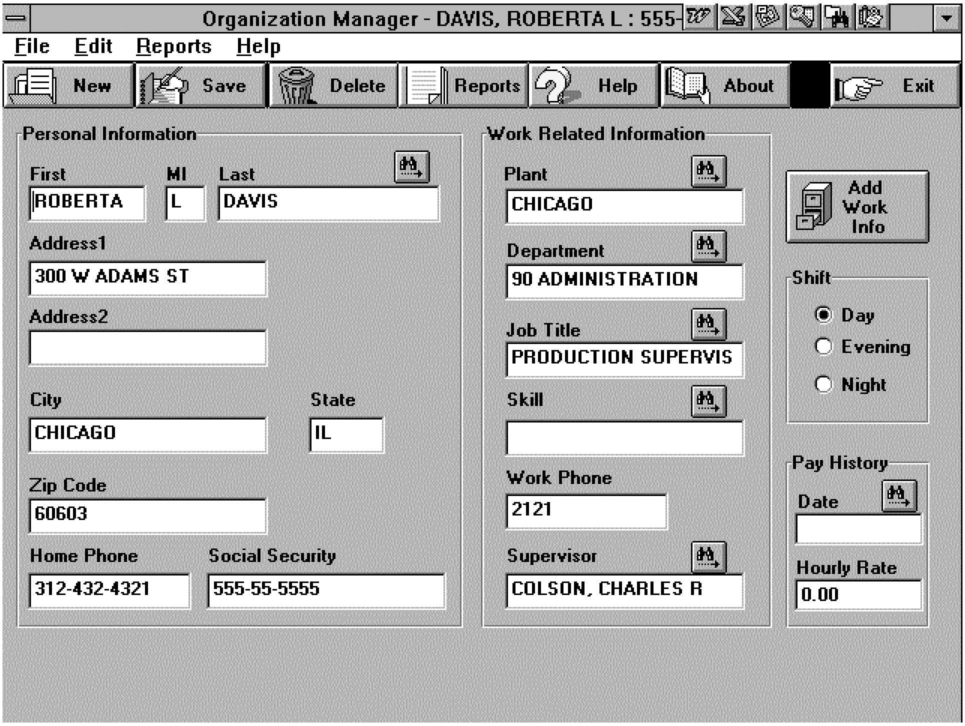
COMPUTER-AIDED MAINTENANCE ORGANIZATION

Maintenance Organization Forms and Ratios

Maintenance Organization Forms. There are two basic forms: *central* and *area.* In a central organization, all work orders are controlled from a central shop. In an area organization, work control is delegated to area shops. Most small maintenance organizations use the central shop concept because it offers better control. Most large organizations use the area shop concept because it offers faster response keeping key equipment running. The area-central organization is a combination of the first two. Skills such as welders, machinists, and painters are dispatched from the central shop. Skills such as mechanics and electricians are assigned to specific areas sufficient to maintain high reliability of key equipment. Other skills not needed there daily are dispatched from the central shop as needed to support the assigned staffing.

Maintenance Organization Ratios. Ordinarily, a good ratio of maintenance workers to supervision is 15:1 if a formal planner function exists. A *planner* defines work content, along with materials and tools needed to do the job. A good ratio of workers to planners is 30:1. Therefore, an effective maintenance team is 30 workers, two supervisors, and one planner. General supervisors usually have four line supervisors reporting to them. One maintenance engineer and one material coordinator are required to support 100 maintenance workers. Ratios are adhered to in smaller organizations by employing combined functions such as supervisor-engineer and planner-material coordinator. The effect of scope of responsibility on ratios must be considered carefully. A supervisor with no planning function and a crew of 15, who spends half of the day hunting for materials, is actually working with a craft ratio of 15:½, or 30:1, leaving only half of the shift for direct crew supervision. The effect of skill of supervision and workers and the nature of the workload also affect ratios. A trained, experienced crew that is assigned preventive maintenance routes or is working at fixed locations in a central machine shop may require only one supervisor for 20 or 30 workers. Formal planning support is needed to perform the field checking to determine the work requirements, plan the material and tool needs, and assign job times using engineered maintenance standards.

Computer-Aided Table of Organization. To develop a new CMMS, management first enters employee information in the organization module of the software. (See Fig. 16.1.2.)



First: ROBERTA
MI: L
Last: DAVIS
Address1: 300 W ADAMS ST
Address2:
City: CHICAGO
State: IL
Zip Code: 60603
Home Phone: 312-432-4321
Social Security: 555-55-5555

Plant: CHICAGO
Department: 90 ADMINISTRATION
Job Title: PRODUCTION SUPERVIS
Skill:
Work Phone: 2121
Supervisor: COLSON, CHARLES R

Shift
● Day
○ Evening
○ Night

Date:
Hourly Rate: 0.00

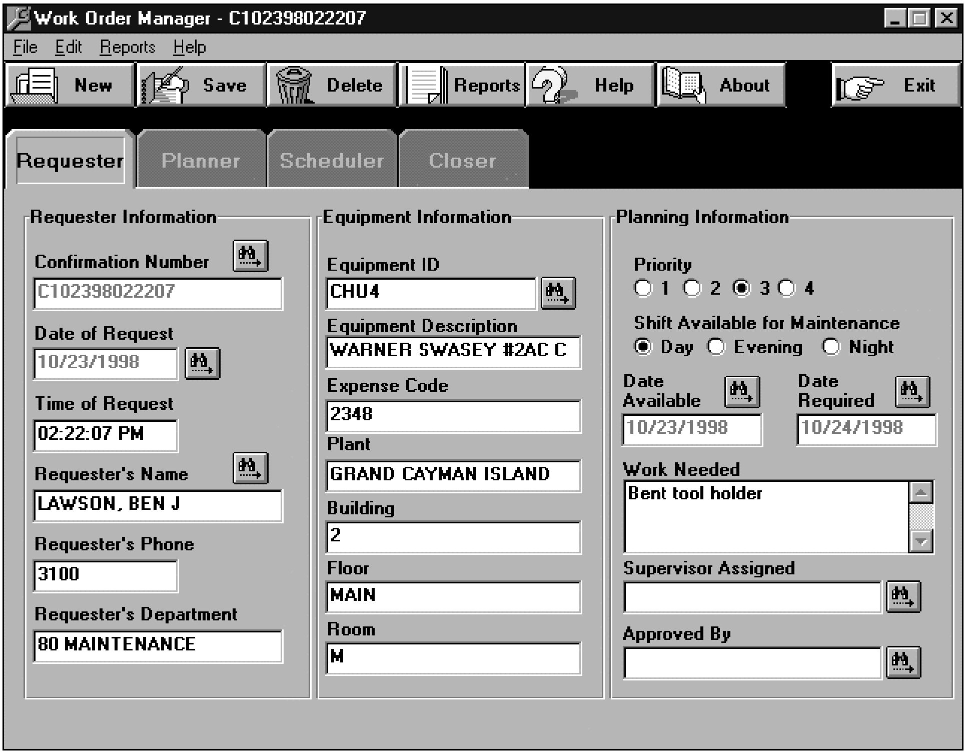
FIGURE 16.1.2 Table of organization data entry screen. (*Reprinted with permission from Productivity Network, Inc.*)

Organization information is entered only once. After this initial entry, the planner selects from a drop-down list individual supervisor or worker names for work orders. Labor hourly rates are added to allow labor cost tracking by work order and equipment item. Reports are generated from the table of organization showing the staffing by supervisor and call-out lists for emergencies or when planning overtime distribution.

COMPUTER-AIDED MAINTENANCE WORK PLANNING

Computer-Aided Work Requests for Paperless Communication of Maintenance Needs

Maintenance work requests are often initiated by a person untrained in maintenance techniques. The objective of the work request is to communicate needs to maintenance. The number of authorized requesters determines how many computer request stations and where they are located. Management delegates maintenance requesting to operating supervisors who are appointed maintenance coordinators for each key operating department. All requests filter through this function to eliminate failure to communicate or duplicate requests for the same work. If the maintenance coordinator is trained in good techniques, requests for poorly conceived work are minimized. For example, equipment modification that benefits one shift or department but will not work in another is less likely. A paperless work request system (see Fig. 16.1.3) eliminates manually writing requests. They are received immediately by the main-



Requester Information

Confirmation Number: C102398022207

Date of Request: 10/23/1998

Time of Request: 02:22:07 PM

Requester's Name: LAWSON, BEN J

Requester's Phone: 3100

Requester's Department: 80 MAINTENANCE

Equipment Information

Equipment ID: CHU4

Equipment Description: WARNER SWASEY #2AC C

Expense Code: 2348

Plant: GRAND CAYMAN ISLAND

Building: 2

Floor: MAIN

Room: M

Planning Information

Priority: ○ 1 ○ 2 ● 3 ○ 4

Shift Available for Maintenance: ● Day ○ Evening ○ Night

Date Available: 10/23/1998

Date Required: 10/24/1998

Work Needed: Bent tool holder

Supervisor Assigned:

Approved By:

FIGURE 16.1.3 Paperless work request screen. (*Reprinted with permission from Productivity Network, Inc.*)

tenance department on the same local or wide area network (LAN or WAN) or over the Internet with no delivery delay. It eliminates duplication that would occur if a handwritten request is again typed into the system. It can utilize multifield, simultaneous entry. When the requester points and clicks on their name, the name, department, phone extension, work request number, and date are filled in instantly. In most cases, entry, approval, and delivery of the request are accomplished in a few seconds in an up-to-date system. Once approved, the work request becomes a work order.

Paperless Work Order. The maintenance supervisor approves the request and assigns a planner, automatically transmitting the request to the planner. The planner, who is a trained, highly experienced former maintenance technician, field-checks the job; completes the often incomplete work description; verifies priority; adds safety, materials, tools, equipment, skills, time, and crew size; and assigns the individual workers on the date scheduled. The supervisor places the work order in a job assignment board with other work to fully utilize each worker for the entire shift. At each stage of the planning process, the work order gains more complete information (see Fig. 16.1.3) with no duplication of effort. As each work order is completed, it becomes a fresh source of feedback that provides facts for physical plant continuous improvement.

Computer-Aided Checklist Work Orders for High-Frequency Maintenance Tasks. The average work order takes an hour to complete. Surveys show that 80 percent of the work orders account for only 20 percent of the labor hours. The computer process that controls this 80 percent of the *work orders* must be efficient, quick, and practical, so that most of the supervisors' and planners' time is focused on the remaining 80 percent of the *work hours.* A separate work order for many less-than-an-hour jobs will require disproportionate administrative effort. On the other hand, any alternative process must retain for supervision a degree of control that promotes effective operations. Blanket work orders with no specific, defined work content do not accomplish this. A weekly checklist work order, assigned to an individual and closed once a week, fits this situation best. Two general groups of work are profitably controlled with the weekly checklist work order: (1) specific daily PM inspection and adjusting routes, and (2) random, high-frequency work such as minor machine and replacing empty air cylinders or burned-out lightbulbs. All employees assigned checklists also have other work orders to utilize their time in between occurrences of the checklist work.

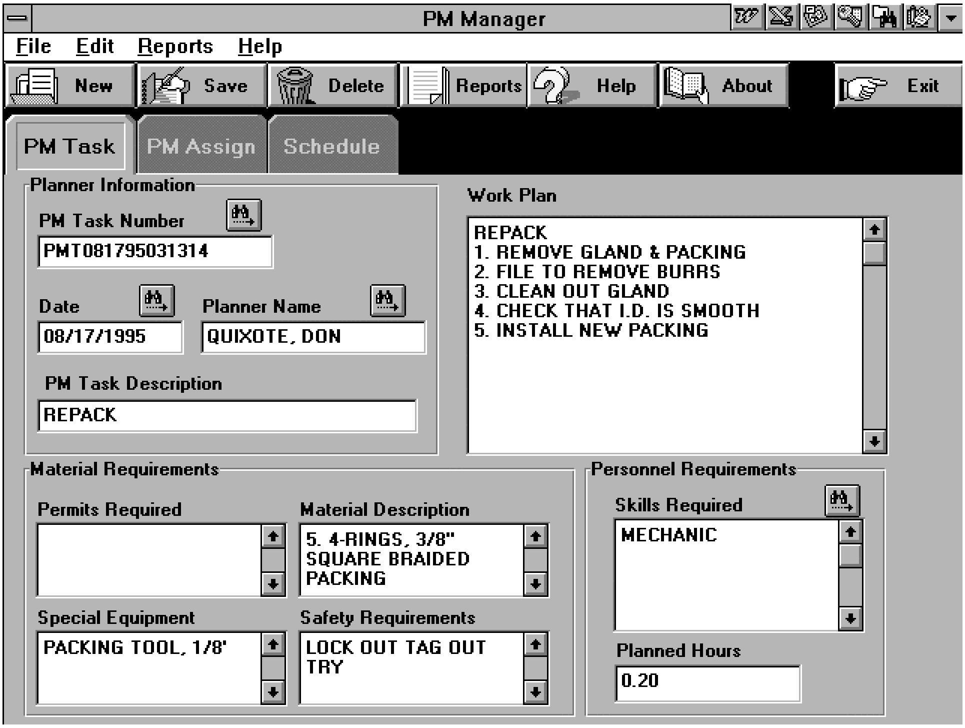
PM Work Planning

As equipment becomes more sophisticated, consequences of downtime become more severe. The foremost concern is safety of the employees near a breakdown. Also, a sudden breakdown may cause major machine damage requiring costly replacement. Another serious effect is disruption of schedules, which can result in customer relations problems or even the loss of an important customer.

Definition of PM. Preventive maintenance (PM) is the systematic planning, scheduling, and completion on schedule of needed maintenance work to ensure the highest availability of equipment and facilities, prolong the useful life of capital assets, and reduce life cycle costs. Preventive maintenance includes inspection, cleaning, lubrication, replacement, or repair and is scheduled annually at regular, preplanned intervals.

Establishing and Maintaining a Computer-Aided PM System. Establishing and maintaining the PM system is divided into the following five steps:

1. Establish the PM task standard procedure for a class of equipment. (See Fig. 16.1.4.)
2. Attach the PM task to specific equipment items.
3. Assign a frequency of occurrence for each equipment item.



Planner Information

PM Task Number: PMT081795031314

Date: 08/17/1995

Planner Name: QUIXOTE, DON

PM Task Description: REPACK

Work Plan:
REPACK
1. REMOVE GLAND & PACKING
2. FILE TO REMOVE BURRS
3. CLEAN OUT GLAND
4. CHECK THAT I.D. IS SMOOTH
5. INSTALL NEW PACKING

Material Requirements

Permits Required:

Material Description: 5. 4-RINGS, 3/8" SQUARE BRAIDED PACKING

Special Equipment: PACKING TOOL, 1/8'

Safety Requirements: LOCK OUT TAG OUT TRY

Personnel Requirements

Skills Required: MECHANIC

Planned Hours: 0.20

FIGURE 16.1.4 Preventive maintenance task screen. (*Reprinted with permission from Productivity Network, Inc.*)

4. Schedule the PM task for an equipment item over an annual time frame.
5. Revise the PM method and/or frequency for changes in equipment usage.

PM Justification Test. Each PM assignment is justified by the following test: Total hours assigned for this equipment item will result in significant benefits—improved quality, yield, equipment availability, asset life, or cost—that will exceed the cost of the PM task.

Predictive Maintenance

Definition of Predictive Maintenance. Predictive maintenance (PdM) is the use of instruments to extend the senses of vision, hearing, and touch to predict which component will fail and when failure will occur. The industrial engineer develops a PdM program to analyze equipment condition, while it is in use, to determine optimum repair intervals and avoid costly, unscheduled downtime.

Advantages of PdM. Some of the key advantages of PdM are as follows:

- Warns of failure before it occurs.
- Measures extent of the substandard condition.
- Identifies cause of impending failure.
- Instruments are portable or fixed.
- Instruments are instant or continuous.

- Condition is measured while the equipment is in use.
- Applies to acceptance tests for new equipment or inspection of existing equipment.

Instruments Used to Perform PdM. Many diagnostic instruments are used in PdM (see Table 16.1.1). All equipment has measurable characteristics such as heat, vibration, noise, electrical signals, and pressure that are in a normal range when the equipment is in good condition, but are outside this range when the equipment is wearing or failing. Industrial engineers use this phenomenon to measure, beyond the range of human senses, the controlling characteristics of systems. With PdM, the equipment is maintained at varying, optimum times, rather than at fixed times. A good CMMS has PdM tracking capability.

PdM Compared with Emergency and Preventive Maintenance. Predictive maintenance is less costly than emergency or preventive maintenance and results in less downtime. Downtime to perform adjustments, repair, and cleaning, when the established metric reaches a predetermined point, is scheduled with no disruption of the operation. In contrast, emergency maintenance is the least safe and the least effective way to maintain the equipment. It costs more and the reliability of the equipment is poor. Loss of equipment availability and production capacity is unrecoverable.

PdM Reduces Inventory. Predictive maintenance reduces inventory cost while increasing material availability when critical spares are required. If management predicts the need for spares more accurately in advance, stores order spares just in time, and inventory turns increase.

PdM for New Equipment Acceptance. The best opportunity for minimizing equipment life cycle cost is before purchase. Proper testing using PdM during the equipment acceptance phase is done under as close to operating conditions as possible to ensure that the equipment will perform well after installation. If the vendor does not have a test facility, the next best approach is to test immediately after installation. Unusual vibration or heat, recorded right

TABLE 16.1.1 Instruments Applied to PdM and Applications for Which They Are Used

Instrument	Application/measurement
Boiler monitors	Start-up; steam, gas, water, pressure; temperature, emissions, firing rate, flow, particulates, rpm, volts, amps
Combustion analyzer	O_2, CO, NO, NO_2, SO_2, hydrocarbons, and pressure
Electric clamp-on meter	ac current, voltage, resistance, continuity, frequency and dc current
Electric current generator	Generate interrupting current, test circuit breakers
Electric power monitor	ac volts, amps, watts, watthour, kilowatthour energy use
Electric tester	Volts, current, frequency, duty cycle, volt and amp waveforms
Fiber-optic meter	Test, maintain fiber-optic cable, detect system loss
Gas leak detector	All combustible gases, natural gas, methane, butane, propane
IAQ analyzer	CO_2 volume, CO, humidity, temperature, differential pressure, air speed, air/fuel ratio, variable controls programmable to match building use cycles
LAN cable meter	Verify LAN cable connection, polarity reversal
Oil analyzer	Oil condition, wear-particle analysis
Process calibrator	Calibrate, troubleshoot process control instrumentation
Refrigerant leak detector	Detect refrigerant loss, maintain documentation
Stroboscope	In-motion inspection, measure rpm
Test specimen	Wall thickness, rate of wear
Thermometer	Electric wiring, contacts, controls; building insulation, roofs
Vibration analyzer	Frequency, amplitude, misalignment, imbalance, worn parts
Video inspection system	Borescope and video camera detect pipeline breaks, obstructions

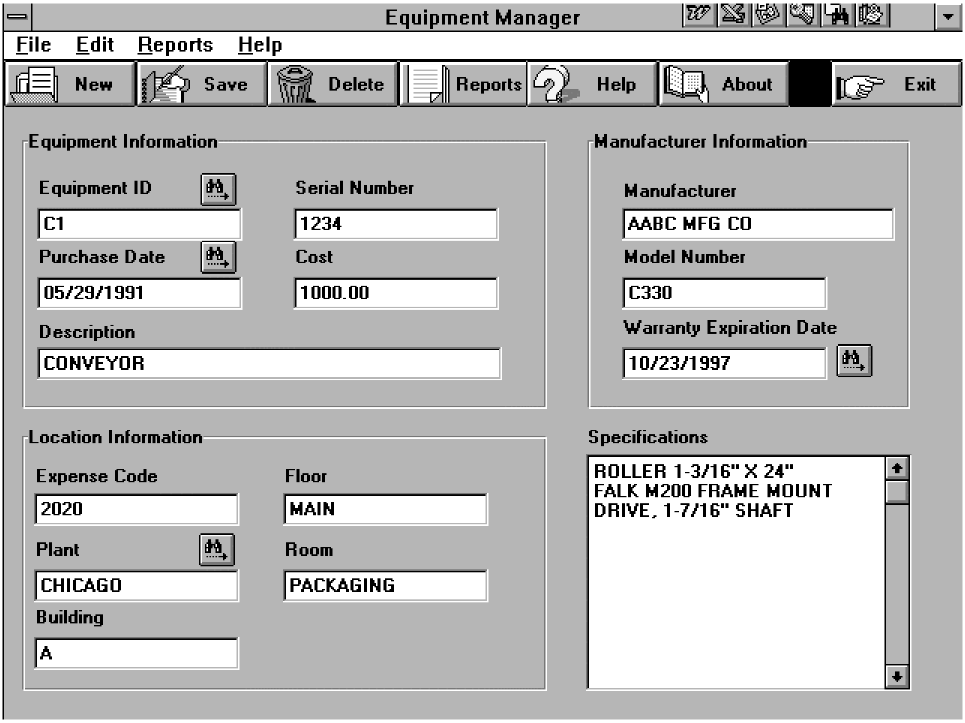
away, can be used to successfully negotiate with the vendor for replacement or redesign of components that show indications of premature failure.

Equipment History Records

The completed work order, properly documented, is the chief source of information for equipment history. In computer systems, the work order time, material, and completion date are entered when the work order is closed, automatically transferring the information to the equipment history.

Features of a Well-Designed Computer-Aided Equipment Record and History System. The first part of a well-designed equipment record system is the one-time entry of equipment specifications. The second part is the periodic updating of the equipment history from closed work orders.

Equipment Specifications. The equipment record (see Fig. 16.1.5) contains the manufacturer's specifications. Each record is assigned an *equipment identification number,* usually alphanumeric, such as PU123 (meaning Pump 123). Other specifications include description (e.g., centrifugal pump), size (e.g., 2 × 3), serial number, model number, manufacturer, and capacity information (e.g., 200 gpm, 35 ft. head, 80 psig). The link between the work order and the equipment record is the equipment identification number. This number is entered into a field in each work order so the closed work order can be filed automatically in the equipment history database. The equipment record also contains a list of key material or component



Equipment ID: C1
Serial Number: 1234
Purchase Date: 05/29/1991
Cost: 1000.00
Description: CONVEYOR
Manufacturer: AABC MFG CO
Model Number: C330
Warranty Expiration Date: 10/23/1997
Expense Code: 2020
Floor: MAIN
Plant: CHICAGO
Room: PACKAGING
Building: A

Specifications:
ROLLER 1-3/16" X 24"
FALK M200 FRAME MOUNT
DRIVE, 1-7/16" SHAFT

FIGURE 16.1.5 Equipment record screen. (*Reprinted with permission from Productivity Network, Inc.*)

specifications, such as spare parts, bearings, sleeves, drive belts, or couplings, which may require replacement later. The list is initially obtained from the vendor parts lists and may be added to or modified as experience demands. After the material specification field is set up, material information can be transferred from the equipment record to the work order without time-consuming reference to vendor catalogs or store inventory records.

Statistical Analysis of Chronological History Determines Maintenance Needs. The industrial engineer analyzes critical equipment histories at least annually to determine the following:

- Total occurrences by type of repair
- Repair labor and material costs this period compared with previous periods
- Total equipment downtime hours and causes in this period compared with previous periods
- Availability and condition of spares
- Need for design improvements (high downtime and repetitive repairs)
- Need for PM improvements (high downtime and repetitive repairs)
- Pareto analysis of equipment cost, from highest to lowest (top 5 or 10 equipment items)

Historical repair information enables the industrial engineer to make good frequency-of-repair, repair-or-replace, and make-or-buy recommendations. Two frequently used statistics are

1. Mean time between failures (MTBF)
2. Mean time to repair (MTTR)

In a successful program, MTBF should be increasing, and MTTR should be decreasing, as shown in Figs. 16.1.6 and 16.1.7. Design improvement, such as a more robust bearing, should require less repair. A repair method improvement, such as use of a power wrench instead of a manual wrench, should reduce the time to repair.

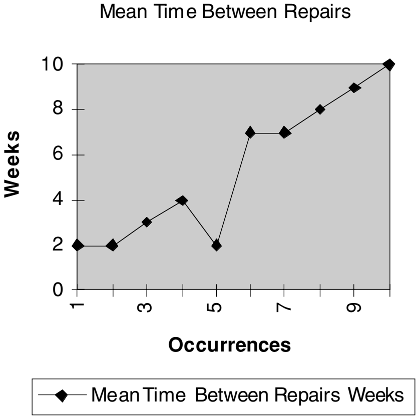


FIGURE 16.1.6 Mean time between repairs trend.

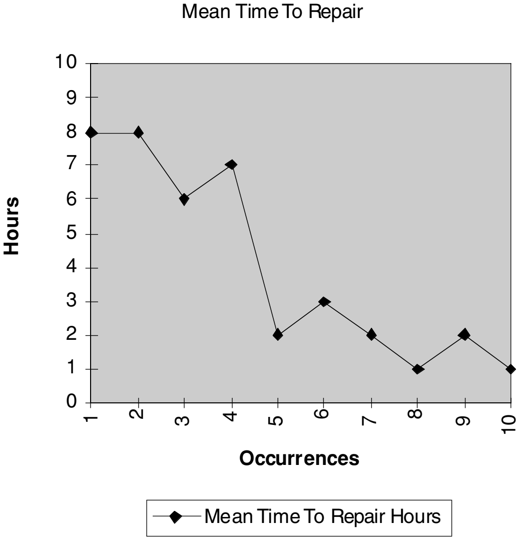


FIGURE 16.1.7 Mean time to repair trend.

COMPUTER-AIDED MAINTENANCE SCHEDULING

Scheduling determines when the work is to be done. The most important supervisor responsibility, scheduling a full day's work for each worker, is best accomplished with a planned backlog of two to four weeks of prioritized work orders.

Role of the Work Order Backlog in Scheduling Maintenance Work

Backlog is the approved maintenance PM, routine repair, and project workload. Backlog is vital to properly distributing the workforce by skill and area among the various work assignments. The optimum backlog range of two to four weeks' work is measured as follows:

$$\text{Backlog weeks} = \frac{\text{total standard (planned) hours}}{\text{number of workers} \times 40 \text{ hours/week}}$$

Example: Assume

$$\text{Total standard (planned) hours of work} = 8000$$

$$\text{Number of workers} = 70$$

$$\text{Backlog weeks} = \frac{8000}{70 \times 40}$$

$$\text{Backlog weeks} = 2.9$$

It will take 2.9 weeks to complete all the work if productivity of the group is 100 percent. When backlog is too high (more than four weeks), jobs are interrupted frequently because failures occur before the needed work can be scheduled. Too many jobs are in progress at a time, and equipment downtime is high. When backlog is too low, time is insufficient for proper planning, jobs are started before they are ready to work, interferences from lack of materials and waiting for job site availability are high, and downtime is also high. High downtime is always a symptom of either too high or too low a backlog level for the workforce. The most common reaction may be, "We don't have enough people to do the work," when the real problem is insufficient planning and lack of good measurement. With proper planning and measurement, more work can be accomplished with a given level of staffing. The industrial engineer, who assists maintenance to establish a backlog system that successfully controls the work order completion, ensures that many other maintenance department management function much easier, such as:

- Weekly and daily schedule preparation
- Prioritizing and approving work orders
- Answering requester inquiries about job status
- Reporting on and expediting material, controlling inventory cost
- On-time work order completion
- Downtime reduction through timely control of small equipment problems

Starting the Work Order Backlog. Five sources of work order information are used to set up the backlog file. They are:

1. Operations requesters, maintenance supervision, and technicians
2. Planned projects from the capital budget
3. Plant or facilities engineering

4. PM/PdM schedules and inspections
5. Vendor installation, operation and maintenance manuals

Managing Work Order Backlog Trends. Since the backlog is constantly changing, management must know whether the trend is increasing or decreasing. The trend of labor hours determines the level and skill distribution of staffing. The backlog chart, prepared from the backlog database file by type of work, displays it. The planner reviews the backlog at least weekly and charts the planned work by type, plus estimated hours on unplanned work. (See Fig. 16.1.8.) Backlog by crew is summarized in the weekly control report. (See Fig. 16.1.15.)

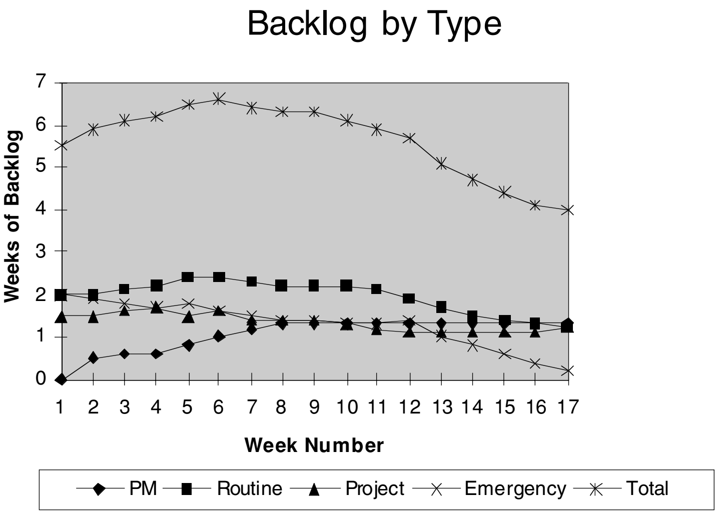


FIGURE 16.1.8 Backlog by type trend.

Weekly Planning and Scheduling

Each week, maintenance, engineering, and production personnel hold a scheduling meeting. Previous results are summarized in the weekly control report. (See Fig. 16.1.15.) Overall priorities are revised. Also, long-range planning of overhauls, plant shutdowns, and individual equipment shutdowns are updated, and schedules for equipment downtime are discussed. From this information, line maintenance supervision establishes detailed daily schedules for specific work orders.

Daily Maintenance Scheduling

From the weekly meetings, maintenance supervision decides how daily schedules will be structured and discusses this with operations. Needs change, priorities change, and equipment availabilities change. If both operations and maintenance keep up to date on these changes, they will coordinate better, and less lost time or delays will result.

A Time-Sensitive Priority System Is Critical to Equipment Reliability

A priority system ensures that the response to a maintenance request is consistent with its urgency. If management decides that immediate response to every production-related repair

COMPUTER-AIDED MAINTENANCE PLANNING, SCHEDULING, AND CONTROL

is essential, labor cost will skyrocket. If a response time of two to four weeks is established, except for certain critical situations, coupled with scheduled repair downtime intervals, higher equipment reliability and much lower maintenance cost will result. A time-sensitive four-level priority system achieves high equipment uptime by ensuring quick response that is consistent with need. Critical maintenance work gets done on time and at a lower cost. (See Fig. 16.1.9.) Continuous priority adjustment is required to keep a balance between workload and workforce. Overtime, up to the policy limit, and staffing adjustment are used to bring the two into closer agreement.

Safety Priority Varies. Worn safety traffic lines are not as high a priority as a missing machine guard. The traffic lines wear gradually, but the guard requires reattachment immediately to prevent injury.

Work Order Priority System

An effective maintenance work order priority system is time sensitive. Each priority category has a specific, preestablished response time. This concept allows maintenance management time to evaluate the backlog of work and the staffing to determine how much work is due during each future time period. This ensures that sufficient lead time exists to take corrective action if the workload and workforce get out of balance.

The following four levels of priority are used to ensure that response to a work request for maintenance service is made according to the urgency of the request:

Priority 1. *Emergency.* Includes emergency work needed to ensure personnel safety, respond to an equipment breakdown that has stopped operations, or where the possibility of major machine damage or adverse effect on quality exists. Response must be immediate. Overtime, if needed to remedy the problem, is automatically approved.

Priority 2. *Urgent.* Must be completed during this shift as soon as a maintenance person is available but does not interrupt other work. Overtime approval is automatic.

Priority 3. *Service is needed within 24 hours.* Specify that service is needed *before the end of a certain shift* by entering the number.

1. For the night shift
2. For the day shift
3. For the afternoon shift

Priority 4. *Scheduled work.* This work can wait more than 24 hours. It includes routine repairs, PM scheduled annually, and projects such as overhauls, installation, and modification. The request must include a date when the equipment will be available and work is to be completed.

Safety Priorities. Safety requirements are extremely important and should receive careful and continuing attention. These requirements will fall into all four categories previously shown, from a safety guard missing (Priority 1) to a wearing stair tread (Priority 4). Priorities should be established for safety work according to the circumstances of each situation. The service request should be clearly marked "SAFETY."

FIGURE 16.1.9 Maintenance work priority system with time sensitivity.

PM/PdM Annual Schedule

The combined support of the PM engineer, the planner, the supervisor, and production control is required for high-PM schedule compliance. The PM engineer and planner keep the PM schedule up to date by adding and updating PM tasks and keeping PM coverage high. When the PM engineer approves the PM task, the planner gives it to the supervisor to schedule. Production control establishes sufficient scheduled downtime for each equipment item so that off-production PM such as adjusting and replacing worn parts can be done before quality, yield, or downtime problems occur.

Setting Up the PM Schedule. An effective PM schedule requires a four-step method as follows:

1. A week before the scheduled date, select next week's PM assignments from the computer database by entering the range of due dates and printing all the PM assignments.
2. Sort PM assignments by planner, by supervisor, then by area (to minimize travel time), and then by off-production (must be done when equipment is scheduled out of service) and on-production (must be done when equipment is running, such as running inspections).
3. Arrange by day of the week. The supervisor assigns the work to individual workers according to their knowledge and skill daily, one day at a time.
4. The worker performs the PM tasks, enters the information required, and lists any other deficiencies found (for later issuance of a new work order).

Schedule Compliance Success Comes One Day at a Time. Preventive maintenance assignments are scheduled at the frequency that is best for the continued equipment reliability, optimum life cycle cost, and long useful asset life. To ensure schedule compliance, the planner schedules only one day at a time. A huge pile of PM assignments on the supervisor's desk will guarantee that the PM will not be done on time because supervision has no time to sort through the pile.

Managing PM Compliance Trends. Another important indicator for measuring PM trends is *percent compliance* with the schedule. Percent compliance is the ratio of PM hours completed compared with the amount scheduled. If 250 standard hours are completed out of 300 scheduled, PM compliance is 83 percent. A report listing all PM assignments missed should be reviewed weekly by plant management. If missed PM does not result in equipment problems, frequency may be too high. If problems do result, a more persistent effort to comply with the schedule must begin. As the PM system is installed, a target for total PM hours should be established. Every 2000 hours of PM work equals one full-time person working on PM 40 hours a week for 50 weeks. If PM requirements are 6000 hours per year, staffing is three full-time maintenance technicians. Industrial engineering tracking of annual hours ensures balanced staffing.

COMPUTER-AIDED MAINTENANCE WORK ASSIGNMENT

Supervisor Uses the Work Order Backlog for Assignment Control

Daily, the planners print work orders and give them to supervision along with the daily schedule on which the supervisor has assigned the individual work orders by priority to each technician. The supervisor loads the job assignment board.

Guidelines for Setting Up and Using a Job Assignment Board. A job assignment board is a high-visibility communication center (see Fig. 16.1.10) used to assign and dispatch work on the shop floor or in the field. It is the transfer point from computer control to technician control through the supervisor. The supervisor places the work orders in the "To start" slot with highest priority in front, lowest priority in back. The worker takes the first work order(s) and moves them to the "In progress" slot to show which job(s) are in progress and where each worker is. The worker places interrupted work order(s) in the "Interrupted" slot, moves the next work order to "In progress," and begins the next job.

Individual Job Assignments

Name	To start	In progress	Interrupted	Complete
A. Jones				
B. Smith				
C. Brown				
D. Fox				
E. Edwards				

FIGURE 16.1.10 Individual job assignment board.

Maintenance Activity Time Reporting. Accurate and complete job time reporting is essential for effective productivity control reports and useful equipment history records. Items reported include actual work time, additional work done and parts used, additional work needed (for creation of future work orders), delays encountered by type and duration, and the status of the job (e.g., complete). Emergency work reporting after the fact is particularly important. It often involves downtime and must be recorded directly into the computer or on a blank work order form for later entry for a complete equipment history. Record analysis can reduce downtime through design improvements or PM routines.

Daily Time Distribution. All paid hours, including work time, nonwork time, and delays, are reported throughout the day on individual work orders—or better, online through real-time data collection tied to the computer. The system automatically totals the reported time and compares it with the paid (clocked-in) time daily on an exception report. Each supervisor must account for any misreported time.

CMMS SCALED TO THE FACILITY SIZE

Single-User Systems for Small Central Shops

Single-user computer systems are best suited for small, centralized maintenance organizations where one planner plans the work for up to 30 maintenance workers from a desktop computer in a central shop with central tool and material stores. Typical single-user system hardware includes at least a 2-GB hard drive, 266 MHz, 486 processor, 32 MB RAM, a CD-ROM drive, and a laser printer. A 30-worker shop has available 240 hours of work per day, 1200 hours per week, 60,000 hours per year. Since the average work order size is 1 hour, the system must generate 60,000 work orders per year for full utilization of the workforce. Soon, the hard drive is full of equipment history and work orders. Older information must be archived yearly to make room on the hard drive and enable the system to maintain fast response. *Archiving* is transferring the older information to another drive or to a tape or CD-ROM backup system. A daily backup procedure and uninterruptible power supply (UPS) ensure that no data will be lost due to electrical outages, computer equipment failure, or excessive line voltage variation from transients or harmonics. Periodic power quality check data is maintained as a part of the PM system.

Multiuser Systems for Large Facilities and Multiple Sites

In large facilities, campuses, or where several distant sites must be linked, multiuser computer systems are required. Several planners, supervisors, engineers, material coordinators, store attendants, and clerks are accessing a common database simultaneously. A large mainframe or minicomputer has been historically used for this purpose. Client/server PC systems are growing in popularity because they are more scalable. Also, hardware networks and application program software are more standard. The open-systems architecture concept is used so connectivity among many users is possible. A LAN can be constructed for a single site or a WAN or ISP can be set up for connecting several distant sites composed of many clients (users stations) served by one server (database storage computer).

Protocols are established through layering of the network operating system. If two planners in different locations try to reserve the last 20-foot length of 1½ × 1½ × ¼-inch angle iron simultaneously, the first planner's order will be accepted. The second planner will see a stock-out on the material status screen and reserve the item from future purchases. The second planner knows that the work order must be held in the backlog until the material is available.

COMPUTER-AIDED MAINTENANCE WORK MEASUREMENT

Maintenance work measurement is a function for which the industrial engineer is particularly well suited. How long should it take to complete the work? Work methods are divided into smaller steps, and predetermined times are applied to each step and totaled to calculate the complete task time. Other less frequently used but increasingly important applications of measurement include auditing the maintenance process and paying maintenance workers according to output.

Definition of Measurement

Maintenance activity measurement is the process of establishing a standard method and time that express quality and quantity of work output expected from a specific amount of labor or machine activity input. Examples of work standards developed for maintenance activities are as follows:

Example 1. Remove and replace rotating element, horizontal-split-case centrifugal pump, size 6 × 8, one mechanic, 3.7 standard hours.

Example 2. Remove and replace single-pole, single-throw electric light wall switch, one electrician, 0.5 standard hours.

Measurement-Control Principle

By comparing actual time with standard time, the industrial engineer can measure performance against standard. Action taken to analyze the variance and correct the cause results in meeting the standard. Through this measurement-control process, management achieves control and continuous method improvement.

Twelve Ways the Industrial Engineer Can Apply Measurement to Maintenance

The industrial engineer can usefully apply work measurement as a rough mental estimate or a carefully developed standard using modern work measurement techniques. Careful measurement provides the most consistent measurement and control over maintenance activity. A summary of the major uses for work measurement in maintenance is as follows:

1. Planning maintenance work requirements
2. Scheduling maintenance work by crew and individual
3. Managing continuous improvement
4. Preparing the annual operating budget
5. Comparison with other periods and other methods
6. Measurement of supervisor and worker performance, coverage, delays, and cost per standard hour
7. Payment of workers according to output
8. Measuring workload backlog by craft, area, and supervisor
9. Planning and scheduling major overhauls and construction projects
10. Contractor performance measurement
11. Identifying training needs
12. Managing staffing needs

Importance of Proper Methods

A *maintenance method* is a specific combination of layout, tools, equipment, material, safety, work conditions, and a standard motion pattern to accomplish a quality task. Before measurement begins, the industrial engineer improves and standardizes methods. Employees are trained to follow the improved standard method. These steps are all integral parts of work standards development. Supervision encourages workers to always follow the standard method.

Quality and Quantity Limits of Acceptability

Quality and quantity limits of acceptability are important policy decisions for measurement and control. How high can the grass grow before cutting? How much paint can chip around exterior trim? How much tamping is needed when backfilling an excavation? How much torque must be used when tightening fasteners? With industrial engineering support, management policies regarding these matters determine the method and have a significant influence on the annual hours and cost of maintenance. Analysis of the computerized history database is the most cost-effective way to carefully plan and review these limits continuously.

Industrial Engineering Development of Universal Maintenance Standards

Since the early 1950s, the *Universal Maintenance Standard* (UMS) technique, developed by H. B. Maynard and Company, has been used to apply engineered standards to maintenance work. Today, in its computerized form, it is the most practical and effective method of establishing and maintaining engineered standards for maintenance work.

UMS Is a Standard Data Approach Customized for Maintenance Application

The UMS is a predetermined time standard data method using the customized principles of work content comparison and range of time to apply work measurement to long-cycle, low-volume, nonrepetitive work such as the work found in maintenance.

Work Content Comparison. If two jobs require nearly identical methods, the time standard calculated for one can be applied to the other. For example, replacing a wall-mounted light switch requires nearly the same work content as replacing a two-plug wall receptacle. The standard time for the light switch can be used for the receptacle job and any other similar job, such as a foot switch or stop-start push-button repair. The jobs used for comparison, called *benchmarks,* are selected to represent a cross section of typical maintenance work. All work can be compared with these typical benchmark jobs, sorted by skill. Using work content comparison, as few as 100 to 200 precise benchmarks per skill can be applied accurately and economically to the entire variety and volume of maintenance work. All skills are covered, including mechanical, machine repair, carpentry, paint, masonry, pipefitting, electrical, metalworking, welding, labor, HVAC, electronics, instrument repair and calibration, machining, and tool and die making and repair.

Range of Time. The range-of-time principle recognizes that maintenance work is much more variable than other types of work. Therefore, rather than an exact time standard, a range of time is used to specify how long a job should take. Pipeline valve replacement may involve removing rusted or painted-over fasteners. Depending on their condition, more or less time is required. Rather than saying the standard is 2 hours and 45 minutes, the UMS approach uses a range of time—for example, 2½ to 3½ hours. The mean time of the range, three hours, represents the range and is the standard time for the job. Over a period of a week, the pluses and minuses average out statistically, so that an overall accuracy of ± 5 percent, with 95 percent confidence, is achieved. This is sufficient for planning, scheduling, and performance measurement, and even incentive payment according to output.

Standard Data Format. The UMS method and time data is developed using a predetermined time system such as Maynard Operation Sequence Technique (MOST), developed in the 1960s by Kjell B. Zandin of H. B. Maynard and Company; MTM, developed by Maynard, Stegmerten, and Schwab in the 1940s; or other predetermined time systems. A typical predetermined time system and standard data arrangement may be viewed as a series of building blocks in the shape of a pyramid, with the predetermined elemental time system as its base. Typical standard data tables from which benchmark times are developed are called *basic operations data.* (See Fig. 16.1.11.) The MaxiMOST standard data worksheet illustrates a matrix of suboperations locator numbers (LCNs) for assembly and disassembly of fasteners with various tools developed from standard data and predetermined basic motion times. Special tables for operations unique to a craft, such as welding or electrical work, are similarly developed for calculating welding manual and arc times and electrical repair.

Standard Work Groups Slot Benchmarks Using the Range-of-Time Concept

Standard work groups are time ranges, called *slots,* into which benchmarks are grouped. Standard work group A is assigned the range of time from 0 to 0.15 hours; group B, from 0.15 to 0.25 hours; and group C, from 0.25 to 0.50 hours. (See Table 16.1.2.) The mean of each range—0.1, 0.2, 0.4, respectively—is applied when assigning job times to work orders.

Computer-Aided Benchmark Development. Benchmarks are contained in a computer database developed by using the benchmark analysis format. (See Fig. 16.1.12.) They are developed by using basic operations or craft operations data to describe each step in the

MaxiMost standard data worksheet

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Move

Walk in area		Body motion	
NO. OF STEPS	LCN	APPLICATION	LCN
3 to 9	1461	1 or 2 bends	
10 to 23	1462	or 1 kneel	1464
24 to 42	1463	Sit or stand	
		Climb on/off	1465
		Up or down	
		ladder/10 rungs	1466
		Door	1520

Assemble/disassemble per threaded fastener

	LCN	
Tool	Complete	Adjust
Screwdriver	1474	1478
Wrench or ratchet	1475	1479
Power tool	1476	1480
Hand	1477	1481

Form

Tool	Application	LCN
Hand	Up to 1 foot	1496
Pliers	Each Loop	1497

Cut

Tool	Application	LCN
Pliers	Up to 2 cuts	1498
Knife	1 cut only	1499
	2 to 7 cuts	1500
Scissors	1 to 3 cuts	1501
	4 to 16 cuts	1502

Examine

Activity	Application	LCN
Inspect	Up to 2 points	1503
Read	Up to 4 words or values	1504
Write	Up to 9 characters	1505

Examine/Measure

Tool	Application	LCN
Folding rule	Up to 3 places	1506
Tape	Each object	1507

Process time/UPPER LIMITS

Seconds	TMU	Allowed TMU	LCN
6.1	170	100	1521
15.1	420	300	1522
27.7	770	600	1523
45.4	1260	1000	1524
70.6	1960	1600	1525

Move/Handle part(s)

Part/size definition	Application	LCN
Light or small	Per action	1467
Medium	Per object	1468
Large or bulky	Per object	1469

Manipulate parts

Line handling	Coil/uncoil	3 coils/10 feet	1470
	Tug	per 3 feet	1471
Push/pull object or cart on surface		Up to 21 feet	1472
Operate button, lever, or knob		Up to 2 actions	1473

Assemble/disassemble/General tool use

Activity	Application	LCN
	Up to 3 finger actions	1482
Turn by hand	Up to 4 wrist actions	1483
	1 to 2 arm actions	1484
	3 to 16 arm actions	1485
	Up to 6 normal actions	1486
Shove or draw	1 heavy action	1487
	2 to 7 heavy actions	1488
Strike with hand	Up to 10 wrist actions	1489
	Up to 5 arm actions	1490
	Up to 10 wrist actions	1491
Strike with hammer	1 to 4 arm actions	1492
	5 to 16 arm actions	1493
Pry with tool	1 to 3 actions	1494
	4 to 16 actions	1495

Surface treat/Apply material

Action	Application	LCN
Wipe with rag	1 to 2 sq. ft.	1508
	3 to 8 sq. ft.	1509
Apply with squirt bottle	1 drop only	1510
	2 to 7 drops	1511
Squeeze tube	up to 12 inch bead	1512
Lubricant or sealant	1 to 2 inches	1513
	3 to 6 inches	1514
Grease gun	Up to 4 actions	1515
Squirt can	Up to 8 squirts	1516
Aerosol can	1 sq. ft.	1517
Tape roll	Per ft/strip	1518

FIGURE 16.1.11 Basic operations data table of common suboperations. (*Reprinted with permission from H. B. Maynard and Company, Inc.*)

method. Adding the individual step times yields the total benchmark time and the standard work group. A sketch may be attached to clarify the work content.

Computer-Aided Spreadsheet Development. A computerized benchmark and spreadsheet database classify benchmarks by skill, task area, and range of time (see Fig. 16.1.13). Some electrical task areas are lamping, wiring and conduit, controls, and motors. All jobs with similar work content are in the same task area and the same time range on the spreadsheets. The computerized spreadsheet provides an easy-to-use format for setting, maintaining, and printing updates of the data. Standard setting is done by comparing the work content on the work order being planned with the work content of similar types of work on the UMS spreadsheets.

Applying Universal Maintenance Standards

Eighty percent of maintenance jobs represent only 20 percent of the maintenance labor hours. This large number of short-duration jobs must be processed quickly so that most of the planning time can be applied to the relatively few large jobs that represent the other 80 percent of the labor hours.

Three Ways to Determine Work Content. The planner determines job work content by (1) reviewing the information from the requester, (2) consulting with supervision, or (3) visiting the job site to gain more information.

Determining the Operations and Applying Standard Times. With a clear picture of the job content, the planner divides content into smaller parts to visualize and evaluate work content and time. Emergency work and troubleshooting cannot be determined before the job is started. The overall work content may be known in a general way, but specific operations can only be predicted after partial disassembly and inspection. In this case, it is best to use a trou-

TABLE 16.1.2 Standard Work Groups

	Hours		
Slot	Min	Mean	Max
A	0.00	0.1	0.15
B	0.15	0.2	0.25
C	0.25	0.4	0.5
D	0.5	0.7	0.9
E	0.9	1.2	1.5
F	1.5	2.0	2.5
G	2.5	3.0	3.5
H	3.5	4.0	4.5
I	4.5	5.0	5.5
J	5.5	6.0	6.5
K	6.5	7.3	8.0
L	8.0	9.0	10.0
M	10.0	11.0	12.0
N	12.0	13.0	14.0
O	14.0	15.0	16.0
P	16.0	17.0	18.0
Q	18.0	19.0	20.0
R	20.0	22.0	24.0
S	24.0	26.0	28.0
T	28.0	30.0	32.0

COMPUTER-AIDED MAINTENANCE PLANNING, SCHEDULING, AND CONTROL

Suboperation method/time report

Description: Install and remove jacking rod SubOp ID: 365

Step	Description	Freq	Crew	Unit time	Total hours
1	Remove bolts.	1	B	0.25690	0.25690
2	Remove plate.	1	B	0.00300	0.00300
3	Set up hydraulic jack.	1	AB	0.04500	0.04500
4	Install jacking rod.	1	AB	0.02200	0.02200
5	Jack out shear pin.	1	AB	0.05700	0.05700
6	Ream shear pin hole.	1	AB	0.19700	0.19700
7	Install shear pin.	1	A	0.05600	0.05600
8	Wait for A.	1	AB	0.00000	0.00000
9	Position plate.	1	B	0.00300	0.00300
10	Install bolts.	1	B	0.02569	0.02569
	Total hours				0.66559
	Clock time				0.51735
	Wait time				0.08469
	Average utilization				**87%**

FIGURE 16.1.12 Benchmark analysis format showing typical job method and time. (*Reprinted with permission from H. B. Maynard and Company, Inc.*)

Craft: Millwright Task: Air Compressors Code: 0295.08

Group A (0.0) 0.1 (< 0.15)	Group B (0.15) 0.2 (< 0.25)	Group C (0.25) 0.4 (< 0.50)
BM# 006 0.12 CREW: 1 CHANGE OUT SIGHT OIL FEEDERS-WORTHINGTON AIR COMPRESSOR	BM# 001 0.16 CREW: 1 COMPRESSOR - JOY - REMOVE AND REPLACE VALVE (1)	BM# 007 0.32 CREW: 1 COMPRESSOR, SMALL-CHECK & INSPECT, ADD OIL
	BM# 005 0.15 CREW: 1 CLEAN AIR INTAKE FILTERS-WORTHINGTON AIR COMPRESS.	BM# 008 0.45 CREW: 1 CHANGE OIL, CRANKCASE - WORTHINGTON AIR COMPRESS.
	BM# 009 0.23 CREW: 1 REMOVE & REPLACE INSPECT. PLATE, WORTHINGTON AIR COMPRESSOR	BM# 010 0.29 CREW: 1 PULL INTERCOOLER PART WAY OUT FOR P.M. (INSPECTION)
	BM# 013 0.24 CREW: 1 INSPECT CROSSHEAD, HI-PRESS, CYLINDER, XLE AIR COMPRESSOR	BM# 012 0.28 CREW: 1 R & R INLET OR DISCHARGE VALVES XLE COMPRESSOR (1) VALVE

FIGURE 16.1.13 Spreadsheet format showing benchmarks slotted by range of time. (*Reprinted with permission from H. B. Maynard and Company, Inc.*)

COMPUTER-AIDED MAINTENANCE PLANNING, SCHEDULING, AND CONTROL

bleshooting time and then plan the job after partial disassembly and inspection. Application is a three-step process: (1) determine the standard work group; (2) add the time for job preparation, travel, cleanup, and allowances; and (3) multiply the total by the allowance factor.

Rapid UMS Application with Computer-Generated Standard-Hour Calculation. The planner selects the UMS time for the work order from the computer-generated standard-hour calculation sheet (see Fig. 16.1.14). Once the four components—travel; preparation; job site time and allowances for personnel; rest and minor, unavoidable delays—are known, they are located on the chart. The total time is picked from the chart. No calculations are required.

Time zone	Job preparation	Crew	A 0.1	B 0.2	C 0.4	D 0.7	E 1.2	F 2
Shop	Simple	1	0.2	0.3	0.6	0.9	1.5	2.5
0	0.08	2	0.3	0.4	0.7	1.0	1.6	2.6
Hours	Average	1	0.3	0.4	0.7	1.0	1.6	2.6
Travel	0.17	2	0.5	0.6	0.9	1.2	1.8	2.8
Time	Complex	1	0.5	0.6	0.9	1.2	1.8	2.8
	0.33	2	0.9	1.0	1.3	1.6	2.2	3.2
Zone #	Simple	1	0.3	0.4	0.6	1.0	1.6	2.5
1								
0.05	0.08	2	0.4	0.5	0.8	1.1	1.7	2.7
Hours	Average	1	0.4	0.5	0.7	1.1	1.7	2.6
Travel	0.17	2	0.6	0.8	1.0	1.4	2.0	2.9
Time	Complex	1	0.6	0.7	0.9	1.3	1.9	2.8
	0.33	2	1.0	1.1	1.4	1.7	2.3	3.3

FIGURE 16.1.14 Standard hours calculation sheet used to select total work order time based on selected travel, preparation, job site time, and allowances. (*Reprinted with permission from Productivity Network, Inc.*)

COMPUTER-AIDED MAINTENANCE PERFORMANCE MANAGEMENT

Control Begins with Policy

The computer provides the only practical means to create a policy and procedure manual for the maintenance department. This important guidance would be unavailable without computer-aided documentation because the amount of time would be prohibitive.

Policy Is Guided by the Mission Statement. A maintenance *mission statement,* integrated with the mission of the enterprise, guides policy. The mission statement may be general: "Our mission is to provide the optimum quantity and quality of maintenance service, safely, on time, and at a reasonable cost." This statement focuses attention of all participants on what the department is trying to accomplish, on what factors are important to the overall mission.

The Industrial Engineer's Role in Goal Setting

The mission is actuated when the mission statement is converted into procedures with quantifiable control indices and goals. The industrial engineer designs step-by-step procedures and goals for continuous improvement. This tells each employee what is expected, and it gives frequent feedback showing performance versus the goals. The mission is the *strategy.* The procedures and controls are the *tactics* used to implement the strategy in the shop and field.

Supervisor's Daily Procedures for Continuous Productivity Improvement

Important actions are described in the standard practice manual for the supervisor to use daily, in close communication with general management, to raise worker productivity. These actions include the following:

- Provide work assignments to fully utilize each worker in the supervisor's crew.
- Check work progress to ensure adherence to safety requirements, proper quantity and quality of output, and proper methods.
- Compare scheduled versus completed jobs, and standard versus actual completion times.
- Establish causes for out-of-line performance. Review accuracy of time reporting.
- Initiate action to eliminate the out-of-line performance in close communication with management.
- Check the previous week's productivity results as soon as reports are available.
- Follow up planned actions and investigate nonachievement using the guidelines provided.
- Talk to the workers to determine attitudes, problems, suggestions, or complaints. Find out what motivates each worker individually.
- Request staff assistance if attendance, attitude, output, quality, or training problems arise.
- Discuss this with management, if all corrective actions have been tried several times without the desired result, then implement personnel disciplinary actions according to company policy with full management support.

When supervisors complain that they do not have time to do these things, it is usually because they spend too much time on nonsupervisory activity such as hunting for parts. In such cases, a formal planning function with a material coordinator will alleviate the problem.

Computer-Aided Control Reports Based on the Standard Hour

Control indices that measure progress toward goals are documented in the standard practice manual. The standard-hour unit of measure enables management to measure such indices as performance versus standard time, amount of work covered by standards, and delays and downtime by cause. Converted into cost per standard hour, it is used to calculate return on investment and payback period achieved by implementing the CMMS.

Industrial Engineer's Role in Implementing the Weekly Control Report

The industrial engineer develops and analyzes the weekly control report and analyzes the labor, material, and overhead budget reports for good control of the maintenance program. The weekly maintenance control report (Fig. 16.1.15) is often used by supervisors and maintenance managers to determine performance results and plan further improvement. It measures value received for wages paid, information unavailable from any other source.

WEEKLY MAINTENANCE CONTROL REPORT

Week ending: 24-Feb-98
WEEK NO. 8

q. Savings this week $4,475
r. Annualized savings $232,717
s. Cumulative savings to date $44,750

	ACTUAL HOURS ON COMPLETED JOBS												EMS HOURS CREDIT			CONTROL INDICES						COST		BACKLOG	
Supervisor	Labor Hours on Planned Work	Labor Hours on Unplanned Work	Delay Hours c							Total Actual Labor Hours	Over-time Hours	Down-time Hours	Hours on Planned Work	Hours on Un-planned Work	Total EMS Hours Credit	% Perfor-mance	% Cover-age	% Delay	% Produc-tivity	% Over-time	% Down time	Total Compen-sation	Cost per Standard Hour	EMS Hrs	Wks
	a	b	1	2	3	4	5	6	Total	d	d1	d2	e	f	g	h	i	j	k	l	l1	m	n	o	p
B. STERLING	400	76	0	0	4	0	0	0	4	480	24	0	375	64	439	94%	84%	1%	91%	5%	5%	$5,174	$11.78	1200	2.7
K. SNOW	180	18	0	0	0	2	0	0	2	200	10		160	14	174	89%	91%	1%	87%	5%	4%	$2,156	$12.36	340	1.9
J. REED	460	54	0	0	4	2	0	0	6	520	40		430	45	475	93%	89%	1%	91%	8%	3%	$5,606	$11.79	1080	2.3
A. BROWN	190	49	0	0	1	0	0	0	1	240	8		170	39	209	89%	79%	0%	87%	3%	6%	$2,587	$12.35	560	2.7
B. JOHNS	1230	197	0	0	9	4	0	0	13	1440	82		1135	164	1299	92%	86%	1%	90%	6%	5%	$15,523	$11.95	3180	2.4

a. Actual hours on planned work from Work Orders [WO's] completed this week
b. Actual hours on unplanned work from WO's
c. Total delay hours from time reporting
1. Wail for instructions
2. Wait other worker
3. Wait for material
c. Total delay hours (Cont'd.)
4. Wait work site or permit
5. Wait tools/equipment
6. Other (meetings, first aid)
d. a+b+c (including overtime) on completed jobs
d1. Hours worked at overtime rate from time reporting
d2. Downtime hours
e. EMS hours produced on planned WO's
f. b × h × 0.90
g. e + f
h. e*100/a
i. a*100/(a + b)
j. c*100/d
k. g*100/d
l. d1*100/d
m. (Reg + O.T. pay) × Fringe factor ($10.78)
n. m/g
o. EMS hours from backlog
p. o/g
q. (Base-n)*g. Base CPSH = $15.40
r. q × 52
s. sum of "q" to date

FIGURE 16.1.15 Weekly control report showing performance management control metrics. (*Reprinted with permission from Productivity Network, Inc.*)

Computer and the Future of Maintenance Management

The weekly control report gives results for a one-week period. Computer-generated control charts show trends of the control indices over longer time periods. Trends give management and supervision more perspective over time. For example, a backlog increase may be short term calling for temporary overtime or a long-term trend calling for an increase in staffing.

Scheduling Performance Trend Reviews

During weekly planning meetings, supervisors will use the weekly control report and other computer database equipment information to review performance results. Preparing for this review and explaining the results is excellent training, which will improve supervision's understanding and control. Hearing the reports of others will give supervisors ideas they can implement in their own areas. Scheduling trend reviews as a part of the regular weekly planning meetings makes continuous improvement an integral part of the day-to-day activity of the maintenance department.

Audits Find Hidden Resources. Periodic operational audits are a frequently overlooked source of continuous improvement opportunities. Because they seek answers to questions not often asked, audits will be used more to reveal hidden secrets about how labor, material, and overhead resources can be stretched further. Industrial engineers find that one of the most frequent laments of maintenance managers is, "I don't have enough staffing to get the work done." An operational assessment may find that 30 percent of the labor hours available are hidden by unproductive practices. See Chap. 4, "Benefits of Auditing," in this section.

Wage Incentives Find More Hidden Resources. Three ways in which the industrial engineer will apply standards to wage incentives in maintenance to increase productivity in the future are

1. *Pay maintenance employees a share of the production bonus.* This is easy to administer and has low up-front development cost; however, maintenance output is usually inverse to production output, and also this approach dilutes the direct workers' bonus.
2. *Use a ratio factor based on direct hours compared with maintenance hours.* Development cost is higher, but it is quick, reflects output of the maintenance department better, and is a good way to optimize staffing for varying levels of production.
3. *Pay each maintenance employee standard hours of maintenance produced multiplied by their individual hourly rate.* This does not dilute direct worker earnings. A weekly calculation levels day-to-day fluctuations. Management can measure performance, determine delay causes, measure backlog, and calculate proper staffing levels. Performance can be measured individually or in groups. This method has a high, one-time initial development cost, but also the highest return on the investment and a short payback period. The motivational impact of added earnings potential consistently produces at least 20 percent greater output than a measured daywork system, which pays a flat hourly rate regardless of output.

Automation and rapidly increasing government-mandated work practices are making all enterprises more capital intensive and less labor intensive. The future will see a much greater reliance on the wealth of computer information for better, more cost-effective resource use.

FURTHER READING

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Internet Resources

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www.plant-maintenance.com (Multiple sources)
www.hbmaynard.com (H. B. Maynard and Company, Inc.)
www.pninc.com (Productivity Network, Inc.)

BIOGRAPHY

Thomas A. Westerkamp is a partner and director at Productivity Network, Inc., management consultants, based in Lombard, Illinois. His consulting career spans over 30 years during which he has directed and conducted many maintenance improvement programs. He has managed a fully integrated maintenance and construction function as a plant engineer. He holds a Bachelor of Science in Industrial Engineering from the University of Dayton, Dayton, Ohio, and is a Senior Member of the Institute of Industrial Engineers. He has conducted seminars at national and international maintenance conferences, written over 50 articles on maintenance, is currently a contributing editor for *Maintenance Solutions* magazine, and authored *Maintenance Manager's Standard Manual,* Second Edition (Prentice-Hall, Paramus, NJ, 1997).

CHAPTER 16.2

BENEFITS OF AUDITING THE MAINTENANCE DEPARTMENT

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An operational audit of the maintenance system is performed to evaluate and assess the current effectiveness of the maintenance department. The audit results focus on identifying improvements, scoping a reengineering program, or acting as a catalyst for a continuous improvement program so vital to successful maintenance management today. Enterprises as diverse as metalworking, chemical processing, health care, education, commercial operations, government, food processing, and electronics can benefit from a maintenance audit. Therefore, this case study is a composite that is typical of audits conducted in all these businesses. This audit process is based on success factors in over 300 maintenance improvement programs conducted in diverse operations throughout North America, South America, United Kingdom, Scandinavia, Continental Europe, and the Caribbean. This chapter describes an audit approach based on fundamental management principles. The audit utilizes state-of-the-art software to quantify the effectiveness of the current maintenance organization and maintenance management processes. The audit enables management to evaluate the improvement potential, including savings, and identify and prioritize specific improvement actions. When improvements are implemented, the organization achieves much higher productivity, greater quantity and quality of maintenance service, and much lower cost. A predetermined, documented payback, included in the audit software, helps sell the program to higher management and track improvement implementation results.

BACKGROUND AND SITUATION ANALYSIS

Background

A *maintenance audit* is defined as the assessment and evaluation of the maintenance process to determine the present method of managing the workload and the workforce, to identify improvements to the present method, and to develop an improvement plan with specific projects, responsibilities, and a timeline to realize that potential.

A maintenance department has responsibility for the proper, reliable, safe operation of the physical plant of a business enterprise. This responsibility is the same whether the enterprise is engaged in manufacturing, health care, education, government, or commercial activity. The common need of all audited operations was reliable facilities and equipment with which business could be conducted in a safe manner and at a reasonable cost. When maintenance was discussed, the industrial engineer often was asked the following questions:

- Why evaluate our maintenance process?
- Where do we start to assess our program?
- How good is our maintenance work management?
- Are there hidden resources we are not using effectively?
- What improvements are best for our maintenance management program?
- What questions should be asked in each audit?
- How do we evaluate the audit results?
- How will we calculate the potential savings/cost of productivity improvement?
- Is our computer system hardware and software supporting the maintenance process?

Situation Analysis

Maintenance audits were not performed with regular frequency in maintenance organizations that were audited. When major problems such as too many equipment breakdowns occurred, the tendency was to look at the organization structure and staffing changes for solutions. Typical organization changes made were the following: assign maintenance personnel to high downtime areas reporting to operations management, assign all maintenance personnel to operations or production departments, add maintenance workers, or reduce the maintenance workforce because some maintenance people were idle when observed by management. These actions did not achieve the desired result, or the result was limited and short term. Many of the same or even worse problems appeared. Most of the time, both the process and the organization were the problem, so organization changes alone did not solve the problem. If the actions taken were based on factual information and resulted from application of tested principles and processes, they were more likely to achieve desired results.

Why Evaluate Your Maintenance Process?

Historically, while organizations have not performed maintenance audits annually, they have performed financial audits regularly. Financial audits have been a legal requirement for public companies since the Great Depression in the 1930s so vividly impressed on many businesses the consequences of not doing so. Not auditing maintenance operations is shortsighted. Typically, an operational audit of the maintenance department was done because management perceived maintenance as affecting operations in a negative way. Scheduled activity was interfered with due to equipment problems, customer service was interrupted, costs were too high, and operations were interrupted too often.

In addition, the industrial engineer may have looked at the need for a maintenance audit from the work measurement perspective. Was the overall productivity level of the maintenance department low, indicating cost reduction potential? What was labor utilization and performance? Other functions looked at the maintenance problem from other perspectives. General management and finance wanted better return on capital investment, lower cost of goods sold, or higher return on revenue. Production management evaluated the maintenance function from the equipment reliability perspective, wanting zero downtime regardless of the cost. Too much downtime was occurring because of changeovers, setups, and mechanical repair. Maintenance management looked at the function from the perspective of getting more work done with limited resources, often using costly overtime to catch up. Government wanted more service to the public at a reasonable cost. Effectively selling the need for the

BENEFITS OF AUDITING THE MAINTENANCE DEPARTMENT

audit considered all these perspectives because support from all the major organization groups was needed. This support and active participation by all the organization's functions ensured not only gaining approval to perform the audit, but also getting the best information available from all sources.

OBJECTIVES AND SCOPE

Starting with a clear definition of the objectives and scope of the maintenance audit also enhanced management support.

Where to Start to Assess a Maintenance Program?

The best starting point for audits that were successful was defining clearly the objectives and scope. Both objectives and scope were stated in quantifiable terms. Objectives may be stated as finding ways to do the following:

- Increase return on investment 15 percent
- Reduce downtime to 2 percent or less
- Increase maintenance labor productivity by 20 percent
- Correct problems in the work order system
- Reduce inventory by 20 percent
- Eliminate stock-outs
- Eliminate customer service problems due to equipment failure
- Eliminate quality and yield problems due to equipment failure

Scope was quantified by listing all departments or sections of the maintenance department included. Those areas excluded were also listed:

- Included groups

Electricians	22
Mechanics	41
Custodians	12
Instrument	16
Welders	10
Stores	6
Supervision	8
Total	115

- Excluded groups

Contractors	8

Organization

The organization and processes, which controlled the work of the included groups, were the main factors that drove the groups' effectiveness. A management principle quoted by the vice president of a multinational financial institution asserts: "The organization is the key to success and the system (process) is the solution." A well-trained and experienced organization can handle many complex situations. Further, if they used a proven system comprising detailed standard practices and procedures, designed to deal with any situation, they obtained optimum results. A well-designed organization structure, a process for getting the work done, management controls, and an integrated computer system were essential ingredients. The processes that tied process capability with responsibility were the maintenance organization, work order, equipment history, and PM systems. Those components affected every repair done. A state-of-the-art, structured audit of repairs, conducted regularly, revealed valuable insight that led to continuous improvement. A comprehensive set of audit questions, reviewed regularly, was effective in updating the maintenance department processes, improving the level of maintenance, improving equipment reliability, reducing downtime and cost, and achieving other established objectives.

Maintenance was often the largest indirect operating cost, second only to direct cost of operations. It has been estimated that maintenance cost is in the hundreds of billions of dollars annually in the United States alone. When the cost of construction and modification performed by the maintenance department or contractors under maintenance direction was added, it was many times that amount.

A plant with 100 or so hourly maintenance employees typically had a labor, material, and overhead budget easily in excess of $10 million. This information was obtained from the accounting department at the beginning of the audit. If no budget was available, historical costs were used. How well these dollars were used was a continuing source of concern for higher managers and therefore for plant engineers and maintenance managers, although the latter two were more concerned with functional objectives—getting the work done—than with cost objectives. Ability to measure and control these resources was a high-priority management desire.

Managing the Life of a Work Order

The life of a work order was the focus point in evaluating the maintenance process. It starts with the need for service and follows the flow shown in Fig. 16.2.1. The work order process was examined, including procedures for planning work orders—scheduling, assigning, and completing them—and measuring results. Planning work orders was found to follow a very standard path, as described in the next section, regardless of the type of enterprise.

Planning Work Orders. The person who detected the need for maintenance service, usually an operations, production, or maintenance supervisor or hourly employee, verbally requested most routine service (in an emergency, of course, the request *had* to be verbal). If written, the request, if approved, was delivered to the maintenance shop where further maintenance approvals and prioritizing were required. If not written, a valuable source of analyzing equipment failure causes was lost. Various communications followed, sometimes requiring input from several interested parties. There were many ways to perform a given repair, from a simple fix to a major overhaul. Different methods, parts, and costs were associated with each alternative. Opinions varied widely about priority. It was at this stage that a trip to the jobsite by the maintenance supervisor or worker was often required. Someone—a supervisor, worker, or planner (very seldom found in maintenance organizations)—who understood maintenance and was familiar with the equipment made a field check to evaluate the work content and identify an optimum repair method. Since differences of opinion and judgment enter at this stage, good communication and negotiation skills were necessary. In some cases, the alternatives identified went to a higher authority who acted as a referee and decision maker, and who selected one method as the proper course of action. This further delayed the job.

Once the method was approved, priority, safety needs, permits, tools, equipment, and material were decided. After all the job elements were informally defined, the crew size, trades, or

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Category	Function	Information/Action
Set objectives	Planner	Request Communication Work required Priority Tools Equipment Safety Material Crew size Time Skills
Direct action	Supervisor	Emergency/routine Backlog Schedule Individual assigned Follow-up instructions Completeness/quality Requester communication
Measure results Continuous improvement	Supervisor	Time reporting Performance management Trend analysis

FIGURE 16.2.1 Managing the maintenance activities in the life of a work order.

skills were determined and job time was estimated. Job times are usually estimated (by far the most common method) and are seldom based on engineered maintenance standards. After the planning was completed, the work order was entered into the ready-to-work backlog for assignment, by priority, to a maintenance worker through the supervisor.

Scheduling, Assigning, and Completing Work Orders. The next step was to schedule the job according to priority, assigning as much as a week's work to one individual according to the skill required and the individual crew member's experience. After assignment, the individual decided in what order to do the jobs, and the work was performed. The supervisor follow-up during and after completion to determine completeness and quality was limited, and the requester was seldom notified that the work was done unless the job was urgent. The maintenance worker reported the time and work performed often inaccurately or incompletely, the clerk posted sketchy labor and material information on the equipment record (if a written work order was prepared), and the work order was closed and removed from the backlog.

Measuring Results. Measuring results was seldom accomplished. Various control reports and trend charts that management must use to track performance and identify needed corrective action were not normally available or used infrequently because the information was known to be unreliable. Key report control indicators including performance, coverage, delays, and cost per standard hour produced were unavailable. While the period measured should have been daily or weekly, by crew, area, and total department, no regular measurement of results was done.

Two areas of concern could not be addressed because the control reports were not used: day-to-day performance of the individual crews and cost versus benefit analysis. Measuring results, also accomplished by periodically evaluating the maintenance process through the audit process, comparing the current process to an optimum process, and improving the process in a series of continuous improvement activities, was not possible.

Responsibility, accountability, and authority were not delegated for each step in the life of a work order (see Fig. 16.2.1) in organizations that were not effective. Auditing maintenance department effectiveness and productivity must somehow address each of these activities in the life of a work order to see how well they are done at various points in time and what action can be taken to increase effectiveness. Frequent assessment of these maintenance managing activities has shown new ways by which the maintenance process could be improved. By auditing at least yearly, management achieved and maintained the momentum for continuous improvement and found heretofore hidden resources.

Finding Hidden Resources

The hidden resources that resulted were maintenance hours saved every time (1) an improved method for performing a repetitive maintenance job was devised or (2) the need to do a maintenance job was eliminated by improving the design of the equipment (redesigning equipment to eliminate the failure cause). Each of these opportunities was unique and only the imagination of management and the workers limited the ways resources were freed to be used in other, more productive ways. For example, if a bearing failed often, the engineer selected another, more robust bearing, better adapted to the loads in this particular application or improved the lubrication method or frequency. Every 2000 hours of maintenance eliminated equaled one full-time hourly maintenance worker gained without higher management approval or hiring needed. With continuous improvement, these hidden resources added up very rapidly.

HOW THE AUDIT PROJECT WAS ORGANIZED

Since the industrial engineering department has the responsibility for work measurement, the industrial engineer was assigned the role of audit coordinator. Duties included preparing an audit plan and schedule, contacting other departments for information, delegating information collection responsibility, documenting the information, and summarizing the results. Other duties were reporting results to management in the form of findings, improvement potential, and a plan to implement the improvements and establish a continuous improvement plan based on annual audits.

The enterprise organization chart was consulted to find information sources for answers to various questions in the audit. The questions to be asked (see Appendix, this chapter) were reviewed and the source from whom the information could be obtained was decided. Separated by source, all the questions from one source were requested at the same time. A meeting with each source was held to clarify any questions and decide what format the information should be presented in, whether that format was already available, or what, if any, special queries or report formats were required, and who would prepare them.

Two-Step Continuous Improvement Initiated into the Maintenance Program

Whether the organization had a manual or computer-aided maintenance management system, they were often challenged by the rush of day-to-day events to get more out of the resources they had. Equipment had been added to the physical plant. Typically, it was more complex than before and there were still the same labor resources, or even fewer, to maintain it. The dynamic nature of business operations and the continuous challenge to keep costs down made periodic audit events more and more a necessity if the businesses was to succeed. The audit procedure comprised two major steps. The first step was establishing a baseline, and in the second step, subsequent audits were compared to the baseline to measure improvement trends.

Step 1. The Base Line. The measurement-control principle is one of the fundamental principles of management. To control an activity, you must measure it against some yardstick. That yardstick in maintenance management is the body of knowledge about what makes a superior program, gathered through decades of experimentation and hands-on maintenance management experience.

The maintenance planning, scheduling, and control system was examined and subjected to the right questions about how it rated in terms of a set of success factors. The answers were converted into a quantitative measure of the system's status at any point in time. In effect, a balance sheet was prepared showing the system's assets and liabilities. Then the assets were continued and the liabilities were analyzed to determine improvement actions. The improvements were implemented according to priorities determined as a part of the evaluation process. What actions would produce the most payback the quickest? What critical equipment would benefit the most? How should the problem be approached? What alternatives were there and which one was best? How was success of the intended improvement to be measured? Less downtime? More reliability or quality? Less rework? Less overtime? Lower cost? Better customer service? Most often, the improvement alternative selected offered a broad combination of these benefits and, for this reason, was the one implemented.

Step 2. Annual Evaluation and Comparison with the Baseline. One measurement was not enough to stay on top of the constantly changing situation. Conditions were different as time passed. Priorities, too, changed and needed to be reevaluated. The first survey or evaluation found a lack of management controls. Improved time reporting, a planner function and maintenance method, and time standards were instituted. Regular daily or weekly reports were implemented to enhance maintenance supervision's control. Such reports proved to be very effective for day-to-day control. Substantial improvement was immediately gained. But, over time, some slippage occurred, or the improvement plateaued below the performance goals. For the longer range, an in-depth audit such as the one conducted in step 1 was required at least annually to continue the improvement and ensure the program met the test of time.

PROCEDURES AND APPLICATION TOOLS

Best results were obtained by using standard procedures for conducting the audit. Standard procedures enhanced the ability to compare one audit to the next. Using the same questions also ensured that management did not omit any important areas of the organization or system processes when the audit was conducted. In some cases the audit was conducted manually. Some organizations preferred to use software application tools to greatly accelerate the process—an option used more often as more maintenance organizations installed computer systems.

What Questions Were Asked in Each Audit?

What questions were asked in the first and subsequent audits? There are eight areas, or categories, that defined the maintenance process: organization, training, personnel, planning, cost control, materials, engineering, and facilities. How the organization managed these areas determined its success. Improvement opportunities were identified by the answers to questions in each area. Highlights of each of the eight areas are listed in the following, followed by a method to evaluate audit results and determine savings potential.

Eight Maintenance Management Areas and Audit Questions for Each Area

To perform and score an audit manually, the auditor answered the questions in each of the eight areas by circling point values for the answer that most closely fitted the current situation. The auditor totaled the points, divided by the maximum point total for the area, and multiplied by 100 to find percent productivity score for each area. Or, to save time, the audit software described in this chapter was used. Audit results were saved and compared to later audits to monitor progress of improvements from one audit to the next. The list of questions shown in the Appendix contains the questions asked in each audit, multiple choice answers, and point values credited for each answer.

How Management Evaluated the Audit Results

Each audit resulted in more insight into the maintenance department dynamics and resulted in continued improvement in department effectiveness. There are 80 questions included in the survey with a maximum of 10 points per question (see Appendix) for a total possible score of 800 points distributed among the eight survey areas as shown in Table 16.2.1. The first three areas are related to the people in the organization and represent the largest point total, 230 points (29 percent), in the survey. Organization questions from computerized audit software are shown in Fig. 16.2.2. The people score is weighed heavier than other categories because skilled, well-motivated people can overcome many system shortcomings, but no matter how dazzling the system, poorly organized, trained, or motivated people will not get the best use out of it. They will not understand how to use the system or have the will to make it work.

TABLE 16.2.1 Audit Areas, Maximum Points and Percent of Total Points for Each Area

Area	Points	Percent
Organization	50	6
Training	100	13
Personnel	80	10
Cost control	70	9
Planning	110	14
Materials	110	14
Engineering	180	23
Facilities	100	11
Total	800	100

Source: Productivity Network, Inc. Reprinted with permission.

Management looked at the individual questions and point scores to identify specific items in the system that would offer improvement. For example, if under Planning, they answered the question, “What percent of hours worked is covered by work orders?,” with the answer, “20 percent,” they scored low. Using the guideline of 85 to 90 percent planned and scheduled work, they identified techniques to improve the use of the work order system so that it applied to more of the maintenance work as a needed improvement. That action had a major impact on the program’s success because it immediately resulted in greater control of labor and material resources.

How Were Potential Savings from Productivity Improvement Calculated?

Improving the amount of planned maintenance work meant real dollar savings to the organization. Savings resulting from the improvement were calculated. The key indicator was percent productivity based on the point total your program scored in the next audit as compared to the previous audit and the maximum shown in Fig. 16.2.3.

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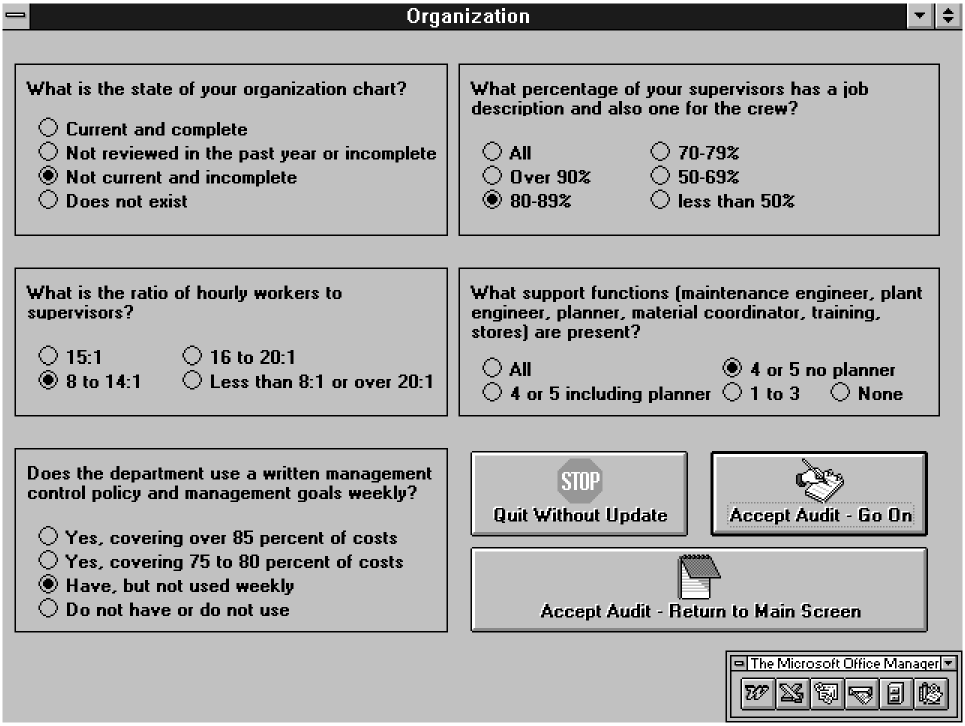


What is the state of your organization chart?

- ○ Current and complete
- ○ Not reviewed in the past year or incomplete
- ● Not current and incomplete
- ○ Does not exist

What percentage of your supervisors has a job description and also one for the crew?

- ○ All
- ○ Over 90%
- ● 80-89%
- ○ 70-79%
- ○ 50-69%
- ○ less than 50%

What is the ratio of hourly workers to supervisors?

- ○ 15:1
- ● 8 to 14:1
- ○ 16 to 20:1
- ○ Less than 8:1 or over 20:1

What support functions (maintenance engineer, plant engineer, planner, material coordinator, training, stores) are present?

- ○ All
- ○ 4 or 5 including planner
- ● 4 or 5 no planner
- ○ 1 to 3
- ○ None

Does the department use a written management control policy and management goals weekly?

- ○ Yes, covering over 85 percent of costs
- ○ Yes, covering 75 to 80 percent of costs
- ● Have, but not used weekly
- ○ Do not have or do not use

STOP
Quit Without Update
Accept Audit - Go On
Accept Audit - Return to Main Screen
The Microsoft Office Manager

FIGURE 16.2.2 Computer screen showing the format used to audit the organization area. (*Reprinted with permission from Productivity Network, Inc.*)

The following example shows how the calculation was done. A typical score for a program with little or no formal planning and no engineered standards was 400 points. This point total is equivalent to 50 percent productivity:

$$\%\ \text{productivity} = \frac{400}{800} \times 100 = 50\%$$

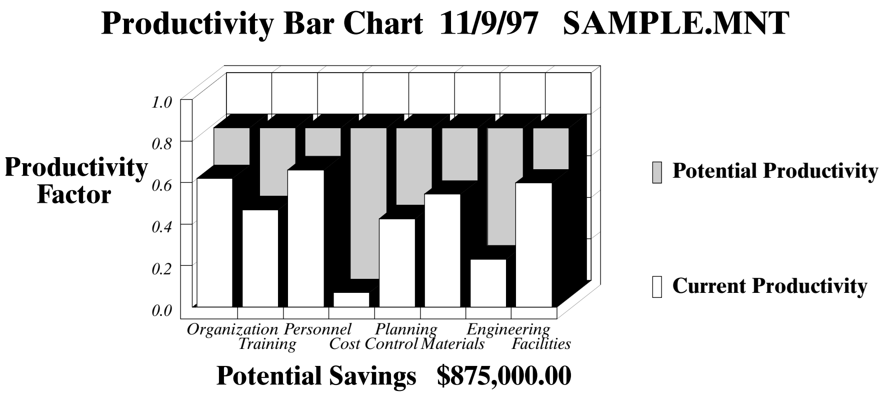


FIGURE 16.2.3 Computer screen showing the scores for the eight audit areas and potential savings. (*Reprinted with permission from Productivity Network, Inc.*)

After management introduced a formal planning function, engineered standards and improved work order planning, and scheduling and reporting—covering 90 percent of the work—productivity increased to at least 80 percent. In an organization with 100 hourly employees in the maintenance department and average wages and fringe costs of $25,000 per year, their savings were as follows:

$$\frac{50}{80} \times 100 = 63 \text{ hourly workers needed at } 80\%$$

$100 - 63 = 37$ workers available for other assignments or staff reduction depending on the backlog of work

$$37 \times \$25{,}000 = \$925{,}000 \text{ savings annually}$$

Regular auditing gave further new insight into greater potential and paved the way for continuous improvement of the maintenance organization, planning, scheduling, and control.

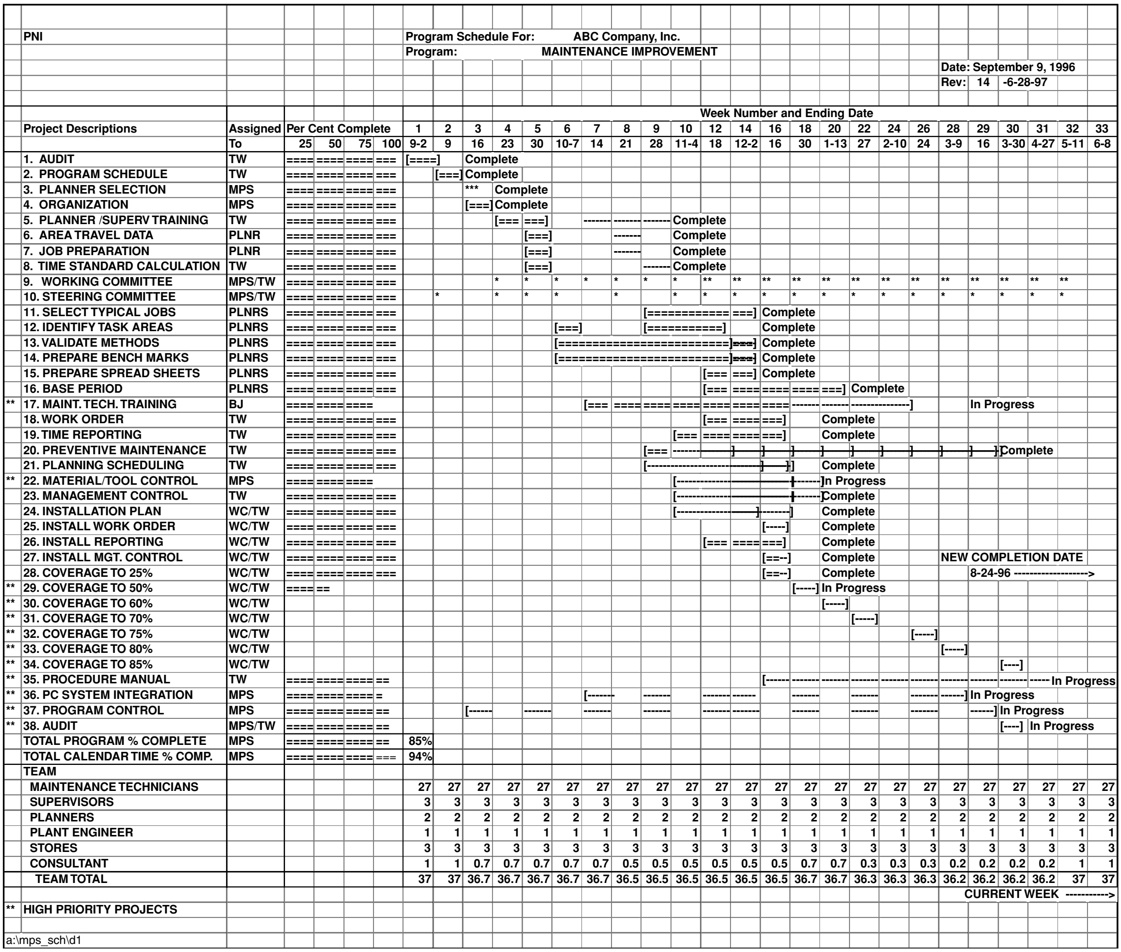
IMPLEMENTATION OF CHANGES AND IMPROVEMENTS

Changes and improvements came from a variety of sources, but the most common was focusing on the planning, scheduling, and control system. A few of the major sources were increased labor productivity, material inventory reduction (and also better material availability), lower overhead costs, downtime reduction, quality improvement, and yield improvement. Each source of improvement required slightly different approaches to implement the change and achieve actual improvement.

How Changes and Improvements in Labor Productivity Were Implemented

The typical situation found was that the greatest potential improvement opportunities were in the areas of planning and work measurement. An improvement program schedule, with defined projects and a timeline, was developed (see Fig. 16.2.4).

Most programs did not have an effective bridge between the work request (often verbal) and the work completion. This bridge is planning. The way this bridge was established was to implement a formal planning section in the maintenance organization. Who would try to manufacture a product or provide a service without an order entry and production control function? Yet it was common in most organizations audited that maintenance supervisors and skilled maintenance workers were expected to remain productive with all the job requests in their memory and to plan their own work, including work content, materials, tools, equipment availability, crew size, job duration, safety, and so on. As a result, many jobs were forgotten and crews lost as much as two-thirds of the day in this planning, leaving only one-third of the shift for wrench time. On the other hand, after a small dedicated planning function was introduced, and the planners trained in effective maintenance planning techniques, wrench time was increased to two-thirds or more, substantially increasing the amount of work performed and enhancing control of work backlog. Planners were selected from the most experienced skilled workers. Some managers were reluctant to do this fearing that loss of these skills would hamper progress of current work. But the reverse was true. By assigning planning duties to these highly skilled people, the skills they possessed were transferred to all maintenance workers through the job plans the new technicians-turned-planners created. Their highly skilled work methods and selection of correct materials and tools, which were part of the new job plans they created, constituted on-the-job training for everyone in the maintenance department, often supervisors included. Before, these skilled workers affected only the jobs they actually worked on. Now, as planners, their skill affected all the jobs done through the plans they created. Typical comments after the planning function was implemented, especially by the less experienced members of the maintenance crews where turnover has been historically high,



	PNI						Program Schedule For:					ABC Company, Inc.																		
							Program:				MAINTENANCE IMPROVEMENT																			
																									Date: September 9, 1996					
																									Rev:	14	-6-28-97			
																	Week Number and Ending Date													
	Project Descriptions	Assigned	Per Cent Complete				1	2	3	4	5	6	7	8	9	10	12	14	16	18	20	22	24	26	28	29	30	31	32	33
		To	25	50	75	100	9-2	9	16	23	30	10-7	14	21	28	11-4	18	12-2	16	30	1-13	27	2-10	24	3-9	16	3-30	4-27	5-11	6-8
	1. AUDIT	TW	====	====	====	===	[====]		Complete																					
	2. PROGRAM SCHEDULE	TW	====	====	====	===		[===]	Complete																					
	3. PLANNER SELECTION	MPS	====	====	====	===			***	Complete																				
	4. ORGANIZATION	MPS	====	====	====	===			[===]	Complete																				
	5. PLANNER /SUPERV TRAINING	TW	====	====	====	===				[===	===]		-------	-------	-------	Complete														
	6. AREA TRAVEL DATA	PLNR	====	====	====	===					[===]			-------		Complete														
	7. JOB PREPARATION	PLNR	====	====	====	===					[===]			-------		Complete														
	8. TIME STANDARD CALCULATION	TW	====	====	====	===					[===]				-------	Complete														
	9. WORKING COMMITTEE	MPS/TW	====	====	====	===				*	*	*	*	*	*	*	**	**	**	**	**	**	**	**	**	**	**	**	**	
	10. STEERING COMMITTEE	MPS/TW	====	====	====	===		*		*	*	*		*		*	*	*	*	*	*	*	*	*	*	*	*	*	*	
	11. SELECT TYPICAL JOBS	PLNRS	====	====	====	===									[===========			===]	Complete											
	12. IDENTIFY TASK AREAS	PLNRS	====	====	====	===						[===]			[===========]				Complete											
	13. VALIDATE METHODS	PLNRS	====	====	====	===						[=======================						]===]	Complete											
	14. PREPARE BENCH MARKS	PLNRS	====	====	====	===						[=======================						]===]	Complete											
	15. PREPARE SPREAD SHEETS	PLNRS	====	====	====	===											[===	===]	Complete											
	16. BASE PERIOD	PLNRS	====	====	====	===											[===	====	====	====	===]	Complete								
**	17. MAINT. TECH. TRAINING	BJ	====	====	====								[===	====	====	====	====	====	====	-------	-------	--------------]				In Progress				
	18. WORK ORDER	TW	====	====	====	===											[===	====	===]		Complete									
	19. TIME REPORTING	TW	====	====	====	===										[===	====	====	===]		Complete									
	20. PREVENTIVE MAINTENANCE	TW	====	====	====	===									[===	-------	-----]	-----]	-----]	-----]	-----]	-----]	-----]	-----]	-----]	-----]	]Complete			
	21. PLANNING SCHEDULING	TW	====	====	====	===									[----------	----------	----------	---------]	----]]		Complete									
**	22. MATERIAL/TOOL CONTROL	MPS	====	====	====											[------------	------------	------------	-----+	------]	In Progress									
	23. MANAGEMENT CONTROL	TW	====	====	====	===										[------------	------------	------------	-----+	------]	Complete									
	24. INSTALLATION PLAN	WC/TW	====	====	====	===										[-----------	-----------	-----]	-------]		Complete									
	25. INSTALL WORK ORDER	WC/TW	====	====	====	===													[-----]		Complete									
	26. INSTALL REPORTING	WC/TW	====	====	====	===											[===	====	===]		Complete									
	27. INSTALL MGT. CONTROL	WC/TW	====	====	====	===													[==--]		Complete				NEW COMPLETION DATE					
	28. COVERAGE TO 25%	WC/TW	====	====	====	===													[==--]		Complete					8-24-96 ------------------->				
**	29. COVERAGE TO 50%	WC/TW	====	==																[-----]	In Progress									
**	30. COVERAGE TO 60%	WC/TW																			[-----]									
**	31. COVERAGE TO 70%	WC/TW																				[-----]								
**	32. COVERAGE TO 75%	WC/TW																						[-----]						
**	33. COVERAGE TO 80%	WC/TW																							[-----]					
**	34. COVERAGE TO 85%	WC/TW																									[----]			
**	35. PROCEDURE MANUAL	TW	====	====	====	==													[------	------	------	------	------	------	------	------	------	-----In Progress		
**	36. PC SYSTEM INTEGRATION	MPS	====	====	====	=							[-------		-------		-------	------		-------		-------		-------	------]	In Progress				
**	37. PROGRAM CONTROL	MPS	====	====	====	==			[------		-------		-------		-------		-------	-------		-------		-------		-------		------]	In Progress			
**	38. AUDIT	MPS/TW	====	====	====	==																					[----]	In Progress		
	TOTAL PROGRAM % COMPLETE	MPS	====	====	====	==	85%																							
	TOTAL CALENDAR TIME % COMP.	MPS	====	====	====	===	94%																							
	TEAM																													
	MAINTENANCE TECHNICIANS						27	27	27	27	27	27	27	27	27	27	27	27	27	27	27	27	27	27	27	27	27	27	27	27
	SUPERVISORS						3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3
	PLANNERS						2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2
	PLANT ENGINEER						1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
	STORES						3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3
	CONSULTANT						1	1	0.7	0.7	0.7	0.7	0.7	0.5	0.5	0.5	0.5	0.5	0.5	0.7	0.7	0.3	0.3	0.3	0.2	0.2	0.2	0.2	1	1
	TEAM TOTAL						37	37	36.7	36.7	36.7	36.7	36.7	36.5	36.5	36.5	36.5	36.5	36.5	36.7	36.7	36.3	36.3	36.3	36.2	36.2	36.2	36.2	37	37
																									CURRENT WEEK ------------>					
**	HIGH PRIORITY PROJECTS																													
a:\mps_sch\d1																														

FIGURE 16.2.4 Maintenance improvement program schedule. (*Reprinted with permission from Productivity Network, Inc.*)

were very positive. The maintenance workers felt the high-quality plans helped them do a better job, reduced delays waiting for supervisory instruction, and took the guesswork out of the job when several repair options were present.

Another major benefit of the dedicated planning function was that it introduced engineered performance standards based on predetermined times. These standards were specially developed for low-frequency, long-duration maintenance work (see Chap. 16.1). Engineered performance standards, also referred to as *universal maintenance standards,* have proved very successful in increasing maintenance productivity for over 40 years. Coupled with an up-to-date computerized maintenance management system (CMMS), they further offered the benefit of a consistent unit of measure for maintenance work, quickly applied, and a comprehensive database of equipment history at a low cost.

Labor productivity improvements began with introduction of a constant basis, or standard, against which performance was measured. The main maintenance measurement method was estimates. Estimates were inconsistent and usually far too generous for productivity measurement, planning, and staffing purposes.

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Once the engineered standards were introduced (Chap. 16.1), the new maintenance planning section assigned standard (or planned) hours to each maintenance work order. The standards compared each supervisor's crew's actual times to standard times for a week and observed performance trends. Two factors influenced success of the standards implementation: (1) high coverage of total labor-hours worked and (2) putting the standard on each work order for supervision and workers to see. The supervisor now knew how much work a crew was expected to do, and the worker was motivated by the goal—standards hours that management expected the job to take.

How Material Inventory Savings Were Achieved

If the audit results showed a low score in the Material area, some improvements were identified in both material and parts availability, and in lower costs by turning inventory more often. Turning inventory more often enabled the maintenance department to use the same quantity of material and spare parts annually while tying up fewer dollars in unused material in the storeroom. For example, the same annual material dollars were spent, but at the six-turns level, the business released \$250,000 (\$500,000 – \$250,000) formerly tied up in maintenance material and supplies.

$$\$500{,}000 \times 3 \text{ turns} = \$1{,}500{,}000 \text{ annual cost}$$

$$\$250{,}000 \times 6 \text{ turns} = \$1{,}500{,}000 \text{ annual cost}$$

Cash flow was improved by \$250,000, so more cash was available for other purposes at any point in the year.

Five Ways to Increase Inventory Turns and Reduce Material Costs. The following practices were used to turn inventory faster and reduce working capital required for materials:

- Work was scheduled ahead. Material was not bought until just before use because planning enabled stores to know when it was needed. This could not be done before when a large percent of the work was emergency or unscheduled work. In that case, the tendency was to overstock "just in case."
- Nearby vendors stocked commodity items such as fasteners and bearings for immediate delivery. Each item they added to their inventory reduced the maintenance department's inventory.
- Predictive maintenance techniques were introduced to identify in advance when equipment would need repair. These repairs were scheduled during nonoperating time, and parts were ordered for delivery only when they would be used right away, eliminating the need to carry them in inventory.
- Electronic catalogs from suppliers were used. Supplier electronic catalogs reduced lead time and shortened the lead time to get material. Price, delivery, and terms were available online immediately, any time of the day.
- Essential equipment components were added to stores. This increased quick availability for repair, with minimum downtime of essential equipment. This practice was justified because it cost less than the more extended downtime if the component were not available.
- Blanks instead of expensive finished parts were stocked. Stocking blanks replaced stocking finished parts. The blanks were finished only as needed for repair. For example, a cold rolled bar that could be machined for several different shafts was stocked instead

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of carrying several different shafts, finished to exact dimensions, for each different application.

How Lost Opportunity Cost Was Controlled

In addition to savings due to labor and material cost reductions identified previously, savings from downtime reduction, improved quality, and production yield added to the total savings potential identified by an audit and was actually saved by the resulting continuous improvement program.

Downtime was frequently identified as a lost opportunity cost. The cost was determined by calculating the value of gross revenue contribution lost due to mechanical failure of the equipment. When labor and equipment were unexpectedly idle, the cost of operations continued while the revenue from operations stopped. Downtime cost was calculated as downtime minutes multiplied by the contribution to gross revenue lost per minute.

$$\text{Downtime } \$ = \text{downtime minutes} \times \text{gross revenue } \$ \text{ per minute}$$

Gross revenue per minute was calculated by dividing total revenue per year by operating minutes per year.

$$\text{Gross revenue per minute} = \text{total revenue } \$/\text{operating minutes}$$

Unscheduled downtime, often actually 20 percent or higher, generally should be less than 5 percent of total scheduled operating time as established by management policy. Some businesses have established a goal of zero mechanical downtime. If a business scheduled two shifts, 40 hours each, 50 weeks a year, operating time was 4000 hours (2 × 40 × 50), or 240,000 minutes per year. Five percent of that may seem like a small amount, but it totals 12,000 minutes over an entire year (0.05 × 240,000), or 48 minutes per day.

Lost opportunity costs due to quality and yield problems were also calculated. These costs were rework and lost output costs due to equipment that did not perform properly. The quality control department checked each machine or equipment item's capability to produce within the specifications set for each product operation. This was done by comparing a random sample of finished parts, subassemblies, or assemblies from each operation with the specifications for that operation. The cost of reworking bad units plus lost yield costs that resulted because the machine was slow or inaccurate was the total loss due to quality and yield problems.

How Total Savings Potential Was Summarized and Presented

The total potential savings was summarized from information gathered during the maintenance program audit. Each savings category was calculated and listed separately, and subtotaled. All of the subtotals—labor, overhead, material, downtime, quality, and yield—were added to produce the final total potential savings. This was the target or goal that management published for the improvement part of the program.

Typical information collected during the audit was as follows:

Hourly maintenance workers	100
Average annual payroll and fringe benefits	$20,000
Productivity	60%

Overhead—supervision	$30,000
Inventory	$500,000
Inventory turns	6
Downtime cost	$700,000
Downtime %	10%
Quality and yield cost of rework due to mechanical causes	$100,000
Rework % of revenue	6%

From the cost information, the potential savings were calculated as follows:

Labor
60 / 80 × 100 = 67 required @ 80% productivity potential
100 – 67 = 33 available for other work or reduction
$20,000 × 33 = $660,000

Overhead
33 / 12 hourly each = 3 supervisors available
3 × $33,000 = $99,000

Material
6 to 3 turns $500,000 × 3 / 6 = included with labor

Downtime
5% / 10% × $700,000 = $350,000

Quality and yield
3% / 6% × $100,000 = $50,000

Total Potential Savings
= $660,000 + $99,000 + $350,000 + $50,000
= $1,159,000

Implementation Costs

Gross savings of this magnitude are not without costs. A typical investment to achieve these savings include planners; engineered standards development; training for supervisors, planners, maintenance technicians, and support staff; software and hardware; and consulting. These costs total $500,000 in a maintenance department of 100 technicians. Still, the return on investment is 2.3 to 1. The payback period is one year after installation starts.

Computer Used to Audit the Maintenance Program

Considerable time was saved using customized maintenance audit application software. Three advantages of using the software were (1) productivity calculations were done automatically, so the audit was completed much faster, (2) questions were the same, enabling comparison from one audit to the next, and (3) audit results were automatically saved for comparison after some improvements identified in the first audit were implemented. This second and third benefit enabled management to track improvement trends over a period of time. The online help screens guided the user through the process of performing the audit, summarized the results, and identified specific improvements to implement. The user stopped at any time, saved the file, and came back to the audit later to finish it.

To calculate savings, the user entered the number of employees, average hourly labor rate, and fringe benefit cost on the summary screen. The screen already contained the current pro-

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ductivity percent, calculated automatically from answers to the questions. The audit summary screen and the print function enabled the user to view or print the summary of audit results. This summary showed the productivity percent, actual and potential, for each of the eight survey areas. It also showed the total potential maintenance labor savings that would result when the actual productivity percent is increased to the potential productivity (80 percent) selected.

RESULTS AND FUTURE ACTIONS

Results of the audit and corrective action initially increased the known backlog of work. Actually the backlog was always there, but was hidden from view because it was not well documented (too many verbal work requests). This hidden backlog represented a large amount of deferred maintenance work that had been the cause of an equally large amount of breakdowns, rework, unscheduled downtime, and quality and yield problems. As more frequent inspections were performed and better preventive maintenance coverage of important equipment and facilities was introduced, breakdowns, and yield and quality problems declined. Scheduled downtime was far less than the unscheduled downtime operations was forced to contend with daily. Planned preventive maintenance windows were added to allow time for inspections, and predictive and preventive maintenance for which the equipment was shut down. The business experienced greater machine reliability, more reliable customer service, better customer satisfaction, and higher profitability.

As management saw the initial benefits, saw the break-even point occur from the investment in maintenance productivity improvement, and communicated this information, they also received and retained the support of higher management. A continuous, fresh source of new improvement projects presented themselves from the inspections and preventive maintenance routines each day. A continuous flow of new improvement ideas were revealed as higher levels of control and savings were achieved. These savings helped finance future improvements, further enhancing the audit, planning, scheduling, and control cycle and ensuring a steady flow of better methods, more savings, and a more reliable, safe, and lower cost physical plant.

The audit process showed frequently that if maintenance had been neglected for some time no amount of preventive maintenance seemed to reduce the breakdowns or other equipment-related problems. Another indicator of long-deferred maintenance was that equipment failure causes were different every day. Many components on the equipment were failing at the same time, making failure analysis difficult or even impossible. Other causes often complicated the problem, such as improper equipment use indicating operator training was needed, product changes that made the equipment design obsolete, need for major rebuild or overhaul to bring the equipment up to A-level condition before PM could be effective, the wrong PM method, or the wrong PM frequency. Often, when the audits first started, many of these contributors to low maintenance level were identified. As the audits continued at that location, small problems were identified earlier and corrected.

As equipment costs have increased over the years, reliability has become even more important. Audits identified more applications for predictive maintenance (using instruments to extend human senses and identify impending failure). By making small improvements in PM routines to include vibration, infrared, or oil analysis checks, future problems were predicted and minor repairs were increasingly performed before failure occurred (see Chap. 16.1).

A winning combination for many maintenance success stories has been regular audits, formal planning, standards, a computerized maintenance management system that integrates capability with responsibility, preventive/predictive maintenance, and effective performance management.

APPENDIX: MAINTENANCE AUDIT QUESTIONS

AREA ONE—Organization

1. What is the status of the organization chart?

a. Current and complete	10
b. Not reviewed in the past year or incomplete	6
c. Not current and incomplete	4
d. None	0

2. Does each supervisor have his or her own and the crew's job descriptions?

a. All	10
b. More than 90 percent	9
c. 80 to 89 percent	8
d. 70 to 79 percent	7
e. 50 to 69 percent	6
f. Less than 50 percent	0

3. What is the ratio of hourly workers to supervision?

a. 15:1	10
b. 8 to 14:1	8
c. 16 to 20:1	8
d. Less than 8:1 or over 20:1	5

4. What support functions—maintenance engineer, plant engineer, planner, material coordinator, training, stores—are present?

a. All	10
b. Four or five, including planner	8
c. Four or five, no planner	6
d. One to three	4
e. None	0

5. Does the department use a written management control policy with management goals on a weekly basis?

a. Yes, covering over 85 percent of costs	10
b. Yes, covering 75 to 85 percent of costs	7
c. Have, but not used weekly	5
d. Do not have or do not use	0

AREA TWO—Training

1. Does a master training plan covering higher management supervision, support, and craft or tradespeople exist?

a. All	10
b. Three	7
c. Two	5
d. One	2
e. None	0

2. Is productivity training included?

a. All	10
b. Three	7
c. Two	5
d. One	2
e. None	0

3. Is management training formal and on-the-job?

a. Both	10
b. On-the-job only	5
c. None	0

4. Who performs training?

a. Staff specialists	6
b. Line management and staff	10
c. Line management and other workers	5
d. None	0

5. Is there formal and on-the-job training for planners?

a. Yes	10
b. On-the-job only	5
c. None	0

6. Does the planner training program include work order planning methods, scheduling, productivity, methods improvement, material planning, project planning, field checking, engineered time standards, standard practices, multicraft planning, preventive maintenance and equipment history, and computer use?

a. All	10
b. 75 percent	7
c. 50 percent	5
d. 25 percent	2
e. None	0

7. Is there formal and on-the-job craft training?

a. Yes	10
b. On-the-job only	5
c. None	0

8. Who performs craft training?

a. Staff only	7
b. Staff plus line management	10
c. Other hourly	5
d. None	0

9. What percent of crafts are included?

a. All	10
b. 75 percent	7
c. 50 percent	5
d. 25 percent	2
e. None	0

10. Are there minimum job skill requirements for each craft job title?

a. All	10
b. 75 percent	7
c. 50 percent	5
d. 25 percent	2
e. None	0

AREA THREE—Personnel

1. What is the overall management-labor climate?

a. Cooperative	10
b. Neutral	7
c. Adversarial	0

2. Randomly select 10 examples of substandard job performance. What percent are caused by attitude as opposed to lack of skill?

a. 100 percent	0
b. 80 to 89 percent	2
c. 60 to 79 percent	4
d. 40 to 59 percent	6
e. 20 to 39 percent	8
f. 0 to 19 percent	10

3. Has a climate survey been conducted recently?

a. Yes	10
b. More than two years ago	5
c. Never	0

4. What is the annual turnover due to quits and discharges?

a. Less than 2 percent	10
b. 3 to 5 percent	7
c. 6 to 10 percent	5
d. More than 10 percent	0

5. What percent of productive hours are lost due to late starts and early quits?

a. Less than 2 percent	10
b. 3 to 5 percent	7
c. 6 to 10 percent	5
d. More than 10 percent	0

6. Was there a strike before settling or during this contract?

a. Yes	0
b. No	10

7. How many grievances have been processed in the last six months as a percentage of total maintenance hourly workers?

a. Less than 2 percent	10
b. 3 to 5 percent	8
c. 6 to 10 percent	6
d. More than 10 percent	0

8. How many grievances were settled at the first step as a percentage of total grievances?

a. All	10
b. 75 percent	7
c. 50 percent	5
d. 25 percent	2
e. None	0

AREA FOUR—Cost Control

1. Do you use shop floor work measurement, budgets, and actual historical cost to control your program?

a. All three	10
b. Budgets and costs	5
c. Costs only	0

2. Which control indices and trends—percentage of downtime, performance, coverage, delays, cost per standard hour, productivity, backlog, level of service, overtime—are used?

a. All	10
b. Seven or eight	7
c. Five or six	5
d. Two to four	2
e. Less than two	0

3. What is the time lag between the end of a period and receipt of control reports?

a. A day or less	10
b. Two to four days	5
c. More than five days	0

4. How often are performance reports prepared?

a. Daily	10
b. Weekly	7
c. Monthly	5
d. Less frequently	0

5. How are job time and work reported?

a. By individual and job	10
b. By day	5
c. By week	3
d. By month or clock in and clock out only	0

6. How is report information summarized?

a. By responsible foremen	10
b. By department or work center	5
c. Total only	0

7. How are reports distributed?

a. To responsible foremen plus summaries to management	10
b. To foremen only	5
c. Not distributed to line organization or not prepared	0

AREA FIVE—Planning

1. What percent of staff-hours worked is covered by a written work order?

a. More than 90 percent	10
b. 80 to 89 percent	8
c. 70 to 79 percent	7
d. 69 percent or less	5
e. None	0

2. What percent of work orders relate to specific job content as opposed to blanket type?

a. More than 90 percent	10
b. 80 to 89 percent	8
c. 70 to 79 percent	7
d. 69 percent or less	5
e. None	0

3. What percent of work orders have enough lead time for planning (2 to 4 weeks)?

a. More than 90 percent	10
b. 80 to 90 percent	8
c. 70 to 79 percent	7
d. 69 percent or less	5
e. None	0

4. What percent of work orders have all the following items preplanned: work content by craft, materials, special tools and equipment, multicraft sequencing, engineered job time standards, jobsite access, scheduled date?

a. More than 90 percent	10
b. 75 to 90 percent	8
c. 60 to 74 percent	6
d. 40 to 59 percent	4
e. Less than 40 percent	2
f. None	0

5. Is all shutdown work preplanned and scheduled?

a. Yes	10
b. Major jobs only	5
c. None	0

6. Does foreman check quality and completeness of every job?

a. Yes	10
b. Most jobs	7
c. Half	5
d. Less than half	0

7. What percent of major equipment has a record of repair history?

a. 100 percent	10
b. 75 percent	7
c. 50 percent	5
d. 25 percent	2
e. None	0

8. How many history records are reviewed at least once a year?

a. All	10
b. 75 percent	7
c. 50 percent	5
d. 25 percent	2
e. None	0

9. What percent of plant equipment is covered by preventive maintenance routines?

a. 100 percent	10
b. 75 percent	7
c. 50 percent	5
d. 25 percent	2
e. None	0

10. What equipment is covered by all of the following reports: downtime trends, PM compliance with schedule, written PM instructions, total PM time, high repair item time?

a. All	10
b. 75 percent	7
c. 50 percent	5
d. 25 percent	2
e. None	0

11. How frequently are the reports prepared?

a. Weekly	10
b. Monthly	7
c. Less frequently	4
d. None	0

AREA SIX—Material

1. Do you have an up-to-date stores catalog?

a. All items except preexpended	10
b. Major items	7
c. Some items	4
d. None	0

2. Do you have a perpetual inventory system for major items and spares?

a. All	10
b. 75 percent	7
c. 50 percent	5
d. 25 percent	2
e. None	0

3. Do you have a two-bin system for high-volume, low-cost preexpended items?

a. All	10
b. 75 percent	7
c. 50 percent	5
d. 25 percent	2
e. None	0

4. Are all except preexpended item withdrawals controlled by use of a withdrawal procedure?

a. All	10
b. 75 percent	7
c. 50 percent	5
d. 25 percent	2
e. None	0

5. Is there a tool control procedure used for all company tools?

a. All	10
b. 75 percent	7
c. 50 percent	5
d. 25 percent	2
e. None	0

6. Are there standard lists of tools provided to individuals by the company and provided by the individual?

a. Yes	10
b. Company only	5
c. Individual only	5
d. Neither	0

7. How many tools are out of service for repair?

a. Less than 5 percent	10
b. 5 to 9 percent	8
c. 10 to 20 percent	7
d. More than 20 percent	0

8. Are economic order quantities calculated?

a. All items	10
b. Most items	7
c. Some items	5
d. None	0

9. Are minimum/maximum levels set and maintained?

a. All	10
b. Most	7
c. Some	5
d. None	0

10. Does purchasing maintain a vendor rating system for suppliers?

a. All	10
b. Most	7
c. Some	5
d. None	0

11. What percent of material orders are delivered on time?

a. 100 percent	10
b. 90 to 99 percent	9
c. 80 to 89 percent	8
d. 70 to 79 percent	7
e. 60 to 69 percent	6
f. 59 percent or less	0

AREA SEVEN—Engineering

1. Reliability engineering is used to control downtime on what percent of your equipment?

a. 100 percent	10
b. 75 percent	7
c. 50 percent	5
d. 25 percent	2
e. None	0

2. What percent of equipment histories are analyzed to statistically determine current mean time between failures (MTBF) and mean time to repair (MTTR)?

a. 100 percent	10
b. 75 percent	7
c. 50 percent	5
d. 25 percent	2
e. None	0

3. What percent of major repair and construction projects has an engineer assigned?

a. 100 percent	10
b. 75 percent	7
c. 50 percent	5
d. 25 percent	2
e. None	0

4. Diagnostic routines (vibration analysis, heat sensing, erosion, corrosion, electrical, gaging gas analysis, etc.) are used on a regular, scheduled basis on what percent of your equipment?

a. Over 95 percent	10
b. 80 to 95 percent	9
c. 60 to 79 percent	7
d. 40 to 59 percent	5
e. Up to 39 percent	2
f. None	0

5. How are maintenance time standards set?

a. Predetermined times, time study, and standard data	10
b. Direct measurement with PDT and time study	6
c. Work sampling	5
d. Estimates	4
e. None	0

6. What application system is used?

a. Slotting and work content comparison	10
b. Direct measurement	5
c. None	0

7. What percent of actual hours worked is covered by time standards?

a. More than 85 percent	10
b. 70 to 85 percent	7
c. Less than 70 percent	4
d. None	0

8. Are job times on the work order for the foreman and hourly employees to see?

a. Both	10
b. Given to foreman only	5
c. Neither	0

9. What percent of maintenance hourly workers are paid by a wage incentive plan tied to output?

a. Over 95 percent	10
b. 80 to 95 percent	9
c. 60 to 79 percent	7
d. 40 to 59 percent	5
e. Less than 40 percent	0

10. What type of incentive plan are you using?

a. Standard hour 1-for-1 individual or small group	10
b. Multifactor or large group	5
c. None	0

11. Which information categories are available in your computer system: payroll, time reporting, work order, job planning, daily scheduling for routine work, long-range scheduling for projects, management control reports, downtime, equipment history, preventive maintenance, stores and material control, statistical analysis, or cost justification?

a. All	10
b. 75 percent	7
c. 50 percent	5
d. 25 percent	2
e. None	0

12. Is your system online?

a. Yes	10
b. Batch	5
c. None	0

13. Does the system match capabilities with individual responsibility?

a. Always	10
b. Most of the time	7
c. Sometimes	5
d. Never	0

14. Are computer reports timely?

a. Weekly or more frequently	10
b. Monthly	5
c. Less often	0

15. Is the information complete and reliable?

a. Always	10
b. Most of the time	7
c. Sometimes	5
d. Never	0

16. Does your security system control who has access to what level?

a. Both	10
b. One	7
c. Inadequate control	5
d. None	0

17. How often is the system backed up

a. Daily	10
b. Weekly	5
c. Less often	0

18. Are memory and disk storage properly sized to support users?

a. Both	10
b. One	7
c. Neither are large enough	0

AREA EIGHT—Facilities

1. Do you have a current plant floor plan?

a. Updated within the last year	10
b. Two to four years old	6
c. Older or none	0

2. How are maintenance shop locations and layouts?

a. Ideal	10
b. Good	8
c. Fair	7
d. Poor	0

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3. How is housekeeping?

a. Superior	10
b. Excellent	9
c. Good	8
d. Fair	7
e. Poor	0

4. Are safety equipment and signs always used?

a. In all areas	10
b. Most areas	7
c. Some areas	2
d. None	0

5. How do you rate availability of equipment and tools considering the crafts needed and workload?

a. Better than average	10
b. Average	7
c. Below average	5

6. What is the average square feet of office space for supervisors and staff?

a. More than 75 square feet per person	10
b. About 75 square feet per person	7
c. Less than 75 square feet per person	5
d. None	0

7. How is lighting for the task performed?

a. Better than average	10
b. Average	7
c. Below average	5
d. Poor	2

8. Are the following services scheduled for maintenance at proper intervals annually? Electric, air, water, gas, steam, sewer, and refuse removal.

a. 100 percent	10
b. 75 percent	7
c. 50 percent	5
d. 25 percent	2
e. None	0

9. What percent of custodial employees are covered by preplanned daily routes and tasks, and engineered standards?

a. Over 95 percent	10
b. 86 to 95 percent	9
c. 66 to 85 percent	7
d. 1 to 65 percent	4
e. None	0

10. Are all cranes, trucks, hoists, and lifting equipment covered by a PM plan?

a. 100 percent	10
b. 75 percent	7
c. 50 percent	5
d. 25 percent	2
e. None	0

FURTHER READING

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BIOGRAPHY

Thomas A. Westerkamp is a partner and director of Productivity Network, Inc., management consultants, based in Lombard, Illinois. His consulting career spans over 30 years during which he has directed and conducted many maintenance improvement programs. He has managed a fully integrated maintenance and construction function as a plant engineer. He holds a Bachelor of Science Industrial Engineering from the University of Dayton, Dayton, Ohio, and is a senior member of the Institute of Industrial Engineers. He has conducted seminars at national and international maintenance conferences, written over 50 articles on maintenance, is currently a contributing editor for *Maintenance Solutions* magazine, and authored *Maintenance Manager's Standard Manual,* second edition, Prentice-Hall, 1997.

CHAPTER 16.3

TOTAL PRODUCTIVE MAINTENANCE

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This chapter discusses the practical benefits of total productive maintenance (TPM) in global competition, some complementary initiatives such as just-in-time (JIT) strategies, and ways to evaluate equipment capabilities. In the final section, future perspectives of TPM in manufacturing will be discussed.

INTRODUCTION

Total productive maintenance (TPM) is a method to improve and enhance manufacturing productivity. It is the practical application of data from equipment availability, schedule attainment, and product quality. Through these measurements, the overall equipment efficiency indicates the best use of resources. TPM is not just a maintenance strategy, but a more comprehensive approach to productivity improvements. To think that TPM is only a maintenance strategy would be to miss the complexity of the concept, and underestimate the potential for improvements.

It should also be noted that TPM can be difficult to understand, particularly from an engineering perspective. Though the basic measures are quite familiar to most people, it is the utilization of these measurements that can be confusing. If we were to visualize a brick wall, it would be easy to measure and define the dimensions of the bricks, but more difficult to quantify the mortar that holds them together. Without the mortar, each brick is independent, without connection to the other bricks. This visualization attempts to illustrate the concept of TPM as it relates to standard engineering measures and practices. Just as the mortar in the wall brings the individual bricks together to form a solid mass of strength with definable performance, TPM brings information and functions together in a comprehensive way to better identify actual performance levels, and better quantify improvement opportunities in manufacturing.

The practical study of total productive maintenance requires minimal technical expertise. If an individual has a fairly good level of mechanical comprehension, basic TPM concepts should prove only moderate challenges. When a practical application is attempted, managerial and engineering expertise will also be necessary. For most managers and engineers, TPM will be a logical application of already understood concepts.

THE WORLD OF TPM

Total productive maintenance is a widely discussed subject. TPM requires patience, understanding, leadership, and a keen eye for details. It can help plant operations to increase productivity and reduce costs. This is achieved through the determination of current manufacturing performance (the baseline), and the opportunities to improve. Through the use of overall equipment efficiency (OEE), the baseline can be compared to competitive performance. For example, if a plant has a performance of 60 percent OEE and the competition has an OEE of 90 percent, there is a 50 percent opportunity for improvement.

The most effective TPM installations usually require modified concepts and technical applications to fit a precise need; most plants will thus need a custom installation specifically designed for a single location. In some facilities, a plant will be operating continuously 7 days per week, 24 hours per day. In another facility, operations will need very different improvements in utilization, performance efficiency, and quality. The personnel, operating philosophies, goals and objectives will likewise be very different. To install TPM in these plants, custom-made, and quite dissimilar installations will be required to meet each plant's specific needs.

The Japanese and TPM

In the 1960s the Japanese developed an improved maintenance process, called *total productive maintenance,* which became quite efficient. The key to their success was the application of inherent concepts within their corporate culture, such as teamwork and long-range planning, which were based on long-term management commitments. Because the culture supported collaboration, the sharing of information, performance levels, and teamwork, TPM was a natural result. Again, equipment maintenance concepts are only a portion of an application of TPM.

The Challenge

Receiving top management support for the installation of TPM can usually be achieved with the right information and an approach that meets their criteria for acceptance. The requirements may include specific timetables for a return on investment (ROI), specific performance improvements, or other economic justifications. The TPM process will require a reasonable investment of time, money, training, and patience. This investment will usually be returned through the favorable results achieved.

In a unionized location, it is essential to involve the union in the discussions from the beginning. Often a sharing of plant performance problems, market conditions, and cost constraints will help to influence union support. These discussions are most successful where at least a moderate level of trust has been developed. It would be an advantage to have a high level of enthusiastic support, but as a minimum, union tolerance is needed.

The practical benefits of TPM (see Fig. 16.3.1) are usually well worth the time and effort, and the financial gains typically exceed the initial investment by a factor of 2 to 4. An ROI of 400 percent is often achieved through investments in process changes, improved tools, better communication, or improved records. On occasion, improvements of this magnitude through improved job design and resource availability have been made. The TPM installation is a key to identifying those circumstances that best develop these levels of improvement. It should thus be remembered that TPM is a practical approach to the optimization and enhancement of manufacturing, it affords the organization a logical method to continuously improve and renew operational efficiency.

- Improved work environment
- Improvements in safety
- Increased pride
- Fewer equipment breakdowns
- Less changeover and setup time
- Lower maintenance costs
- Less maintenance-related downtime
- Fewer equipment caused quality problems
- Improved skills
- High return on investment
- Improved equipment speed
- Capacity to expand
- Job security

FIGURE 16.3.1 TPM—practical benefits.

GLOBAL COMPETITION

Competition today, and into the foreseeable future, is global. Only through the process of meeting and exceeding customer expectations can a company expect to have a secure future. Companies must strive to be the best, constantly improving and renewing their accomplishments. Through the use of TPM, and the inherent continuous improvement concepts, these goals can be realized.

The Quality Olympics

An Olympic athlete knows that it takes hard work and dedication to build enough strength to be able to compete against the world's best athletes. Every company must also focus on the physical conditioning of machinery and equipment to become competitive. Perfect quality, like perfect performance, requires the most perfect machine possible. For example, the manufacture of automobile tires historically has been a very dirty process involving smelly pollutants and numerous chemicals such as carbon black—a finely ground powder similar to graphite. In several European tire plants, conditions have improved to the point that visitors report observing clean conditions such as shining floors, clean air, and bright, cheerful facilities. Such clean, precisely maintained facilities have been transformed through TPM installations. TPM provides the proper plans to develop the right practice and application for each unique company.

Other TPM Applications

Common production techniques include a just-in-time (JIT) element, which is necessary for operational efficiency, quality, and cost control. However, a breakdown in the middle of a JIT run is detrimental to quality, cost, and customer delivery. Through increased utilization of equipment, better monitoring and coordination of planned downtime—as well as better equipment maintenance—will improve dependability, and such breakdowns can to a large extent be avoided. The application of a properly installed TPM process will enhance ongoing efforts in the following areas (without new equipment):

- Just-in-time
- Cycle time reduction
- Setup reduction
- Cost controls
- Skills training
- Teamwork
- Capacity expansion

Capacity

The high utilization of equipment is critical in achieving optimum production capacity. Uptime may be 95 percent or more, usually visible, and is often the only measurement that is reported to management. Studies have shown that in many manufacturing plants 50 to 70 percent utilization of equipment is typical. This often indicates that there are losses that are not defined or reported. These are hidden losses. Most of them are the result of short pauses, delays, and operating speed losses. Through TPM these losses can be determined (i.e., when is the equipment being used in the production of products) and to what standard. The typical equipment performance levels, the actual availability, equipment speed, and loss of products will be clearly identified. Where this data is not precisely known and reported, there is usually additional production capacity available.

Financial Advantages

A properly installed TPM process improves equipment utilization, but the return on investment can be more significant. There are many documented cases of plant closings averted, noncompetitive product costs being made competitive, or improvements of bottom-line profitability. Examples are North American automobile production, European foundry operations, South American oil fields, and Asian electronics factories. Other considerations are the environmental and quality expenses, which can be reduced and better controlled at the same time. Since better-maintained equipment uses less energy, savings in energy consumption can be significant.

Safety

In each location where TPM is installed, equipment becomes the first focus of improvements. When equipment runs better, personnel have fewer problems operating and maintaining it. As a result, the personnel has to enter the operating envelope of the equipment fewer times, and because it is operating better, their risks of injury are reduced. When establishing cleaning procedures for the equipment, one of the first activities in a TPM installation is to identify energy isolation points. Their locations are called out in cleaning procedures, visual identifications are created, and approvals are obtained and documented.

EQUIPMENT

TPM has a number of different definitions, including "productive maintenance involving total participation." The complete definition, though, is much larger than that: TPM permanently improves the overall effectiveness of equipment, with the active involvement of operators. The emphasis is on overall equipment effectiveness (OEE). TPM requires more than the operators, maintenance, and supervision, it also involves engineering, purchasing, management, finance, and often labor relations. Good teamwork between operators, maintenance, and other functions usually produces better results on equipment improvement and the TPM installation.

Equipment Management

When corporate books are examined, the production equipment is normally the largest asset. Even land and buildings may not equal the investment in the plant equipment. High asset uti-

TOTAL PRODUCTIVE MAINTENANCE

lization is key to achieving the return on assets (ROA) that is demanded. Only through optimum equipment utilization, equipment availability, and highly effective equipment performance can top results be attained. Any other level of asset utilization will result in disappointment, and is not world class.

Equipment management is thus required and this will focus and enhance a companywide approach to improving equipment productivity. A phased equipment management approach is the process of focusing efforts to improve the elements of equipment utilization, equipment performance, and equipment availability. These phases are key to moving a company through the installation of TPM:

I. Improvement of existing equipment
II. Maintaining improved equipment or new equipment
III. Procurement of new higher performance equipment

Phase I. Each phase of equipment management contains several steps (see Fig. 16.3.2), which must be carefully considered when planning a TPM installation. The first phase is to improve equipment to its highest level of performance and availability. This is the most important phase of TPM; it may take some time and a fair amount of money (depending on current equipment condition) to accomplish this objective.

Equipment Management
Phase I
Improve equipment to its highest required level of performance and availability

Step 1. Determine existing equipment performance and availability (current OEE).
Step 2. Determine equipment condition.
Step 3. Determine current maintenance (especially PM) performed on equipment.
Step 4. Analyze equipment losses.
Step 5. Develop (and rank) equipment improvement needs and opportunities.
Step 6. Develop setup or changeover improvement needs and opportunities.
Step 7. Execute improvements as planned and scheduled.
Step 8. Check results and continue as required.

FIGURE 16.3.2 Phase I of TPM.

Data and careful planning will be required when beginning this phase, and it is necessary to prioritize the improvement of equipment. With good planning an early break-even point can be accomplished, where savings exceed costs. This can be of utmost importance in some companies, because the potential to quickly improve financial performance should not be underestimated.

Through the first three steps of phase I, data is developed that provides guidance in making and setting priorities. These steps are normally accomplished through a feasibility study, which is discussed in a subsequent section. The final management decision to support and fund a TPM installation is often the result of a properly executed feasibility study. Accurate data, with good early results, can often be the fuel that justifies a TPM installation.

Information from the feasibility study, including data such as breakdown and failure information, allows the TPM teams to analyze equipment losses (step 4) and develop improvements (step 5). The resulting cost-benefit analysis, using throughput, cost, quality, and uptime requirements, will help prioritize improvement projects. The allocation of resources will thus support the greatest return from the right investment.

The setup and changeover improvement opportunities are addressed in step 6 of phase I. Using the same TPM feasibility study groups, possibly with specialized engineering assistance, to analyze setup losses will develop improvements and design changes. The actual activities occur in step 7; this step puts planning into action. The scope and duration of this is influenced heavily by actual equipment condition: Step 7 may take several months or more. In reality, the cycle of analysis and improvement will not end, but becomes the process of continuous improvement.

The resulting gains are analyzed and published in step 8, which is the last step in phase I. Results are compared to baseline data, which provides an effective improvement analysis. Results are thus measured, documented, and communicated to justify the TPM installation and to identify opportunities to improve.

Phase II. In phase II (see Fig. 16.3.3), equipment is maintained at its highest level of performance and availability. Previous improvement of equipment is thus maintained through the entire life of the equipment. There is no substitute for effective preventive maintenance (PM). Predictive maintenance (PDM) may also be useful in finding pending problems and resolving them before they occur.

Equipment Management
Phase II
Maintain equipment at its
highest required level of performance
and availability

Step 1. Develop PM requirements for each machine.
Step 2. Develop lubrication requirements for each machine.
Step 3. Develop cleaning requirements for each machine.
Step 4. Develop PM, lubrication, and cleaning procedures.
Step 5. Develop inspection procedures for each machine.
Step 6. Develop the PM, lubrication, cleaning, and inspection system, including all forms and controls.
Step 7. Develop the PM manual.
Step 8. Execute PM, cleaning, and lubrication as planned and scheduled.
Step 9. Check results and correct as required.

FIGURE 16.3.3 Phase II of TPM.

Complex technical diagnostic equipment is not always necessary; sometimes focusing on good basic practices and procedures can have a good return. Careful inspection will often find hidden defects and avert pending problems. *Cleaning is a tool;* there are few careful inspections that do not include a program of cleaning. *Cleaning is inspection,* which finds pending problems; removing these problems is absolutely necessary to attain high levels of equipment availability.

Often, maintenance personnel are fully occupied with fixing breakdowns, leaving little time to perform PM or equipment inspections. Basic cleaning of equipment on a regular basis allows the identification of many problems that can be averted, and thus never interfere with equipment operation. This will usually require operators to address some minor problems themselves (Fig. 16.3.4).

Operators:

- Can carry out most equipment cleaning functions
- Can assist with equipment inspections
- Can help with equipment diagnostics
- Have better equipment knowledge than management usually believes
- Have a direct impact on quality
- Do understand production problems
- Can be very effective in improving equipment performance
- Are usually quite willing to improve their skills
- Are usually very well motivated to participate in all aspects of production, if allowed

FIGURE 16.3.4 Operators can improve their participation.

Numerous cases have been documented where the cleaning of equipment improves equipment availability, product quality, and production capability. Step 1 of phase II (Fig. 16.3.3) includes the development of an effective preventive maintenance process for each piece of equipment. Basic cleaning, lubrication, and inspections are operator PMs (type 1), which begin the process. More technical, specific maintenance personnel PM activities (type II) are also necessary for the optimum performance of equipment. Lubrication (step 2) and cleaning (step 3) use the same development process. PM checklists, work orders, and scheduling are basic in the development of the PM procedures. Standard planning forms for activities are developed in step 6. Without a plan, the control of PM, lubrication, cleaning, and inspection would be difficult to accomplish, coordinate, evaluate, or to improve. A PM manual makes an excellent reference for specific equipment details, and includes information about skills and training procedures.

From a purely managerial perspective, step 9 is extremely useful: inspections, results, savings, and opportunities are measured and analyzed. This step is also key to the dynamic nature of most successful TPM installations. This way the planning, inspections, training, goals, and financial analysis are regularly adjusted to better meet changing needs of equipment. With a TPM installation, equipment becomes better, requiring the equipment evaluation process to also improve. This dynamic approach is the best way to gain additional improvements.

Phase III

Life Cycle Cost. During the process of installing TPM, a great deal of information will be developed about equipment. This information will include equipment problems, constraints such as bottlenecks, along with some possible solutions. Through the application of TPM data, new equipment can be specified that meets even higher levels of performance while lowering the total cost of equipment (see Fig. 16.3.5). This improves the life cycle cost (LCC), which is the total cost of a piece of equipment from design and purchase through installation, maintenance, operation, obsolescence, and finally disposal of the equipment (see Fig. 16.3.6).

The equipment design step determines up to 80 percent of the machines LCC. At the design step, TPM information can be tremendously valuable. By knowing what the problems are in existing equipment, and the solution to them, problems may be eliminated. Higher per-

Equipment Management
Phase III
Procure (purchase) new equipment
with a defined level of high
performance and low life cycle cost

Step 1. Develop engineering specifications.
Step 2. Get input from operators based on current equipment experience.
Step 3. Get input from maintenance based on current equipment experience.
Step 4. Eliminate past problems.
Step 5. Design in new technology.
Step 6. Design in diagnostics.
Step 7. Design in maintainability (maintenance-free equipment).
Step 8. Start training (operational and maintenance) early.
Step 9. Accept equipment only if it meets or exceeds specifications.

FIGURE 16.3.5 Phase III of TPM.

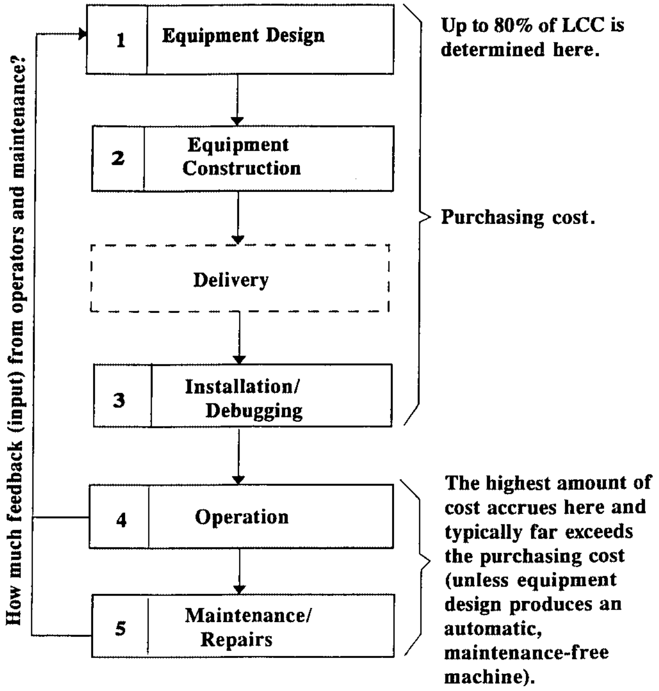

How much feedback (input) from operators and maintenance?
1
Equipment Design
2
Equipment Construction
Delivery
3
Installation/ Debugging
4
Operation
5
Maintenance/ Repairs
Up to 80% of LCC is determined here.
Purchasing cost.
The highest amount of cost accrues here and typically far exceeds the purchasing cost (unless equipment design produces an automatic, maintenance-free machine).

FIGURE 16.3.6 Life cycle costs.

formance with lower costs may well make a big difference on the profit and loss statement. TPM can therefore be a key financial resource in the competitive world of business.

Though the equipment design stage determines up to 80 percent of the LCC (such as quality of equipment and the degree of automation), it is at the operations and maintenance steps that the highest expenses accrue. Design is not independent of operations and maintenance. Through the process of a TPM implementation, this interdependency can be leveraged, eventually reducing costs, enhancing equipment performance, and improving corporate financial performance. In phase III, the people who know the most about the machines contribute to the continuous improvement of equipment design, and indirectly improve long-term profitability.

Diagnostics

Sometimes simple diagnostics designed into new equipment, such as those in an automobile, can simplify the elimination of equipment problems. Current technology is producing highly accurate, low-cost, and dependable instruments that can identify and alert personnel of pending problems. When new equipment is specified, TPM data can provide engineering with this kind of precise specification.

TPM Goals

If equipment performance is to be improved to its highest level, and made easy to maintain, it can't just be approached in a general way. TPM goals are needed to set a consistent direction for TPM installation; these deliberately ambitious goals are known as the *three zeros:*

1. Zero unplanned equipment downtime
2. Zero equipment-caused defects
3. Zero loss of equipment speed

The first goal is probably the most challenging. Though, at first glance, it might sound impossible, it is being accomplished; the key word is *planned.* How much time is devoted to planned downtime, such as planned maintenance, predictive maintenance, cleaning, lubrication, inspection, and adjustments? These are planned activities that will allow equipment to improve toward the zero unplanned downtime targets.

Nearly zero unplanned downtime is not only possible but also probable through a dedication to planning. The exact requirements for planned equipment downtime will usually require less time than originally anticipated, if it is done with discipline and operator participation.

The second goal is *zero equipment-caused defects*—simply high-quality products. Equipment is the barrier to achieving this zero. Equipment must be in a condition that will not cause defects. Remember that perfect quality demands perfect equipment. Any company that is serious about quality must be just as serious about equipment condition.

Hidden losses, the ones that are in the third zero, are things such as loss of equipment speed and idle time. In most companies equipment speed, or cycle time, is rarely compared to the actual specifications and achievable optimum yield. The theoretical or specified speed is often an unknown. Speed losses can be the result of worn, poorly adjusted, or poorly maintained equipment. On many machines, speed losses of 10 percent are commonly found. This means that the company is losing 10 percent productivity (on this machine), increasing cost of manufacturing, and giving up 10 percent of capacity. When a slow machine is in a process line, it will slow the entire line, gradually at first, but over time the slowdown can become excessive.

The Installation Elements of TPM

As mentioned previously, one approach used very successfully in non-Japanese plants involves the use of equipment management. Equipment management has three components:

- Autonomous maintenance (by operators)
- Preventive maintenance (including predictive technologies)
- Equipment management (focus on equipment)

Autonomous maintenance (AM) coordinates, trains, and involves the operators in the care and maintenance of their equipment. This way autonomous maintenance has been adapted for use in the Western companies. The AM approach is flexible enough for differences of culture, facility, union, or managerial issues to be adapted into TPM installations.

The degree of autonomous maintenance is determined by the small group structure, as shown in Fig. 16.3.7. Without some involvement and interest from TPM groups, a TPM installation would be very difficult. This process allows needed flexibility for more successful Western world applications.

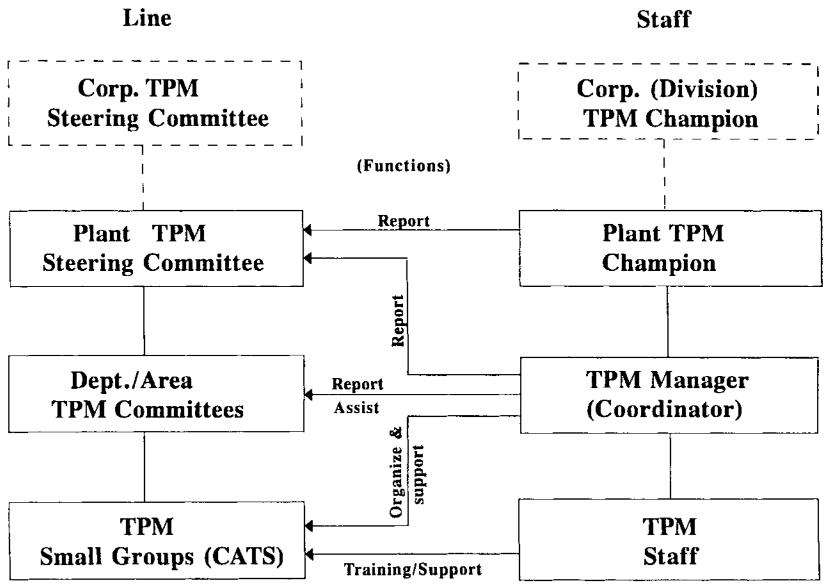

Line
Staff
Corp. TPM Steering Committee
Corp. (Division) TPM Champion
(Functions)
Plant TPM Steering Committee
Report
Plant TPM Champion
Report
Dept./Area TPM Committees
Report
Assist
TPM Manager (Coordinator)
Organize & support
TPM Small Groups (CATS)
Training/Support
TPM Staff

FIGURE 16.3.7 Typical TPM organization.

Equipment needs care. Preventive maintenance (PM) includes both preventive and predictive maintenance, both part of planned maintenance. There may be some overlap between AM and PM since operators must participate in the care of their equipment. With adequate planning and training, operators can eventually begin executing type 1 (operator) PM activities in an autonomous fashion. But a good PM process is important regardless of the level of operator involvement.

Equipment management (EM) is a successful approach for quick success, and is usually seen as far less threatening by personnel. It provides a shared purpose for teamwork, while allowing participants to contribute to equipment improvements. For these reasons, we recommend installing TPM by concentrating on EM first. The improvement of equipment performance and operator involvement are both quickly achieved, contributing a very profitable period during the TPM installation. Early equipment improvements may also provide some good indication of the talent level within each plant. The EM step produces a good foundation to install PM and AM activities, as well.

The coordination of the installation becomes the job of the TPM manager. Dedication to supporting the TPM organization, including the TPM manager, must come from top management. To successfully install TPM, the organizational structure must also be ready to support the efforts. The importance of a proper TPM structure can be easily underestimated by those not familiar with TPM and its potential. Therefore, the TPM small groups, as well as the top management, must support the TPM organization. Top management must also participate in the plant steering committee, with the TPM manager who coordinates the different groups and activities.

The TPM manager, sometimes called the TPM coordinator, is the trainer, facilitator, and coordinator of the TPM installation. In a large facility, a staff to support the TPM manager might be required.

THE FEASIBILITY STUDY

The installation of TPM in different locations requires different approaches. Even installations in similar plants of the same company can require an entirely different solution to work well.

Often the idea of TPM begins with someone at the operational level; the concept must usually be sold to management. To make an effective sale to management, a feasibility study is helpful. After a feasibility study is conducted, the documentation and financial potential will determine the potential for TPM.

In locations that are unionized, there may be some hesitation to accept TPM; however, records indicate that half of all installations in the United States are in unionized locations. Unions, like management, now tend to recognize the positive benefits of a TPM installation, such as increased job security, competitiveness, better skills, and higher profitability, which improves wages. A TPM installation will have a profound impact on a corporate culture. For that reason, it is necessary to obtain the best possible information in advance and then use it to develop custom-made plans for an installation.

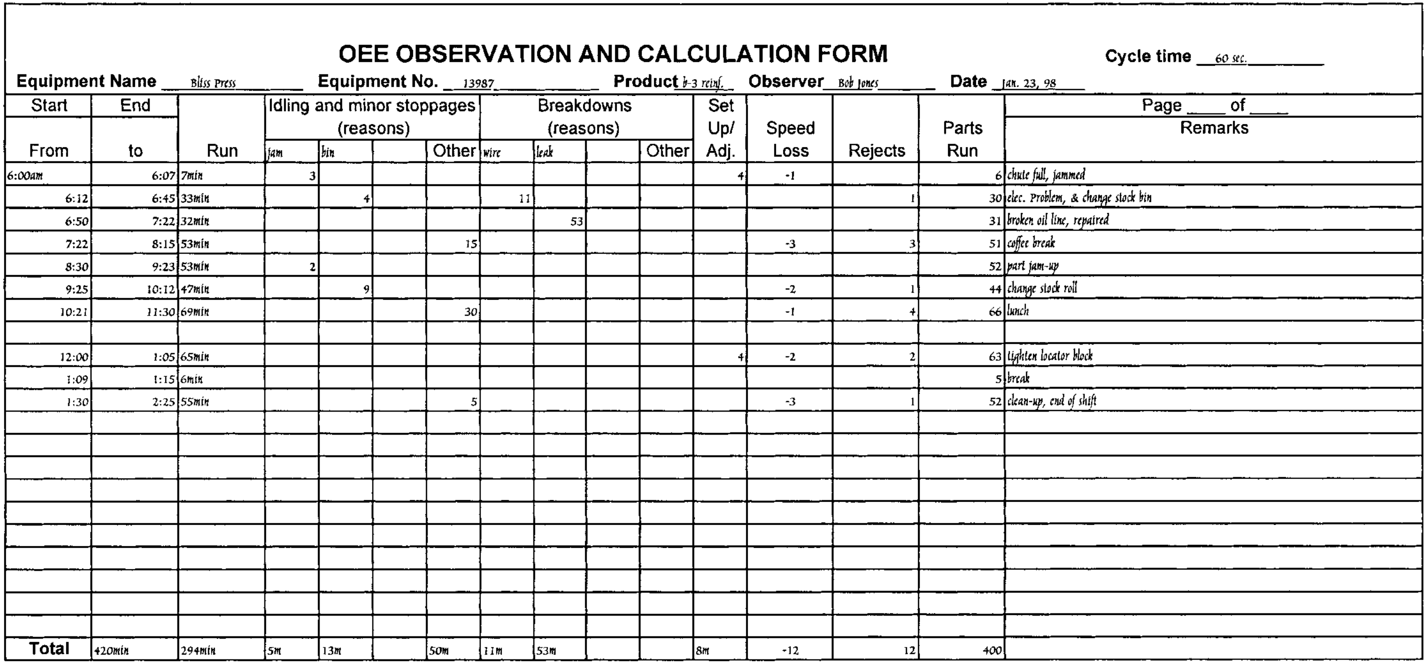
Feasibility Study Tasks

There are two key elements in a feasibility study: One is equipment, and the other is personnel. The feasibility study will focus on these elements. Basically, it is necessary to include important machines and a representative sample of the other equipment. The feasibility team comprises operators, maintenance, and engineering personnel.

The goal is to determine the equipment effectiveness and, in particular, the equipment losses that are part of normal operations. The study will observe the equipment and document any breakdowns, idle time and short stoppages, setups or changeovers, speed losses, rejects or rework, and so forth. Through the process of detailed observations, losses can be recorded, and the calculation of the real overall equipment effectiveness (OEE) is possible. With real knowledge of OEE, the potential for additional availability, production volumes, and quality can be quantified. The feasibility study team will produce data that can demonstrate production and economic potentials.

To organize all the precise data, specialized forms are used. These forms allow for quick data collection, with minimal interference to operations. As Fig. 16.3.8 illustrates, the forms are quickly understood, simple to use, and very effective with minimal practice.

The feasibility study is important not just because it justifies the installation of TPM, but because of its focus on equipment. It's not uncommon for early results from a feasibility study to find improvements that pay for the entire TPM installation. In addition, the required baseline (historic) information is developed for all key equipment. This baseline information determines the initial condition of equipment and clearly shows the equipment losses, the



OEE OBSERVATION AND CALCULATION FORM

Cycle time 60 sec.

Equipment Name Bliss Press Equipment No. 13987 Product b-3 reinf. Observer Bob Jones Date Jan. 23, 98

Start	End		Idling and minor stoppages (reasons)				Breakdowns (reasons)				Set Up/ Adj.	Speed Loss	Rejects	Parts Run	Page ____ of ____
From	to	Run	jam	bin		Other	wire	leak		Other					Remarks
6:00am	6:07	7min	3								4	-1		6	chute full, jammed
6:12	6:45	33min		4			11						1	30	elec. Problem, & change stock bin
6:50	7:22	32min						53						31	broken oil line, repaired
7:22	8:15	53min				15						-3	3	51	coffee break
8:30	9:23	53min	2											52	part jam-up
9:25	10:12	47min		9								-2	1	44	change stock roll
10:21	11:30	69min				30						-1	4	66	lunch
12:00	1:05	65min									4	-2	2	63	tighten locator block
1:09	1:15	6min												5	break
1:30	2:25	55min				5						-3	1	52	clean-up, end of shift
Total	420min	294min	5m	13m		50m	11m	53m			8m	-12	12	400	

FIGURE 16.3.8 OEE observations. (*Reprinted by permission of the International TPM Institute, Inc.*)

potential improvements, and provides a benchmark of success after improvements have been carried out. Later, when TPM has been used for a period of time, having good baseline data from the feasibility study will be a useful reference.

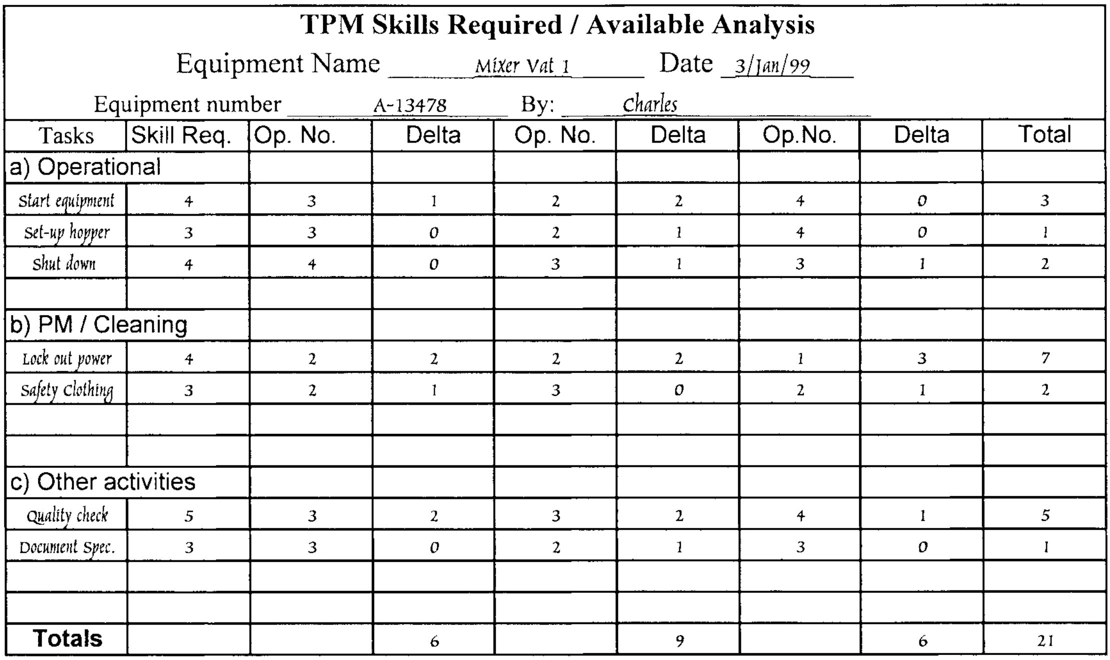
Specialized TPM Forms

Baseline studies include documentation through specialized forms. Basic examples are included here and should provide more information than could be simply described. These include:

- *OEE observation and calculation form,* for equipment improvements and reduction of losses (Fig. 16.3.8)
- *Skills analysis,* for current operator training competence and training requirements (Fig. 16.3.9)
- *Maintenance assessment,* for current type and amount of maintenance and future needs (Fig. 16.3.10)
- *Housekeeping survey,* how the work area appears (Fig. 16.3.11)
- *Cost analysis,* for savings calculations, which vary depending on product, process, and financial information (Fig. 16.3.12)

Through a properly done feasibility study, a TPM installation can be justified to the most cost-conscious critic (see Fig. 16.3.13). A well-constructed TPM feasibility study will help to define required TPM tasks and priorities. This then will aid the development of a custom-made TPM installation plan.

The examples shared here are deliberately abbreviated. The observation and documenta-



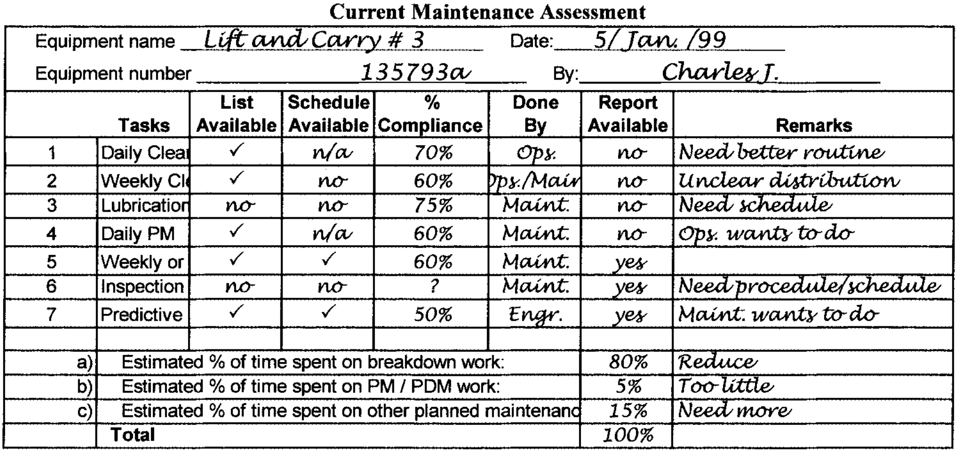
TPM Skills Required / Available Analysis

Equipment Name Mixer Vat 1 Date 3/Jan/99

Equipment number A-13478 By: Charles

Tasks	Skill Req.	Op. No.	Delta	Op. No.	Delta	Op.No.	Delta	Total
a) Operational								
Start equipment	4	3	1	2	2	4	0	3
Set-up hopper	3	3	0	2	1	4	0	1
Shut down	4	4	0	3	1	3	1	2
b) PM / Cleaning								
Lock out power	4	2	2	2	2	1	3	7
Safety clothing	3	2	1	3	0	2	1	2
c) Other activities								
Quality check	5	3	2	3	2	4	1	5
Document Spec.	3	3	0	2	1	3	0	1
Totals			6		9		6	21

FIGURE 16.3.9 Basic skills analysis. (*Reprinted by permission of the International TPM Institute, Inc.*)



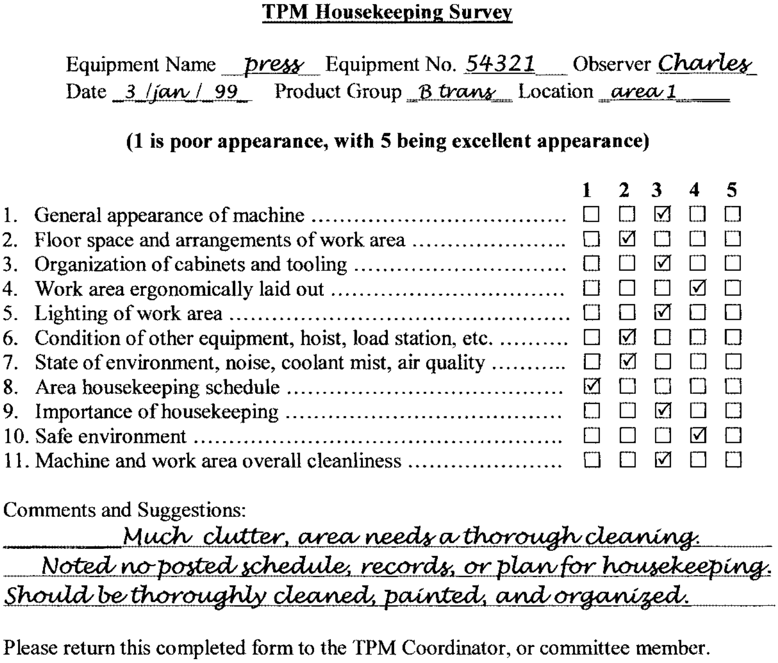
Current Maintenance Assessment

Equipment name Lift and Carry # 3 Date: 5/ Jan. /99

Equipment number 135793a By: Charles J.

	Tasks	List Available	Schedule Available	% Compliance	Done By	Report Available	Remarks
1	Daily Clea	✓	n/a	70%	Ops.	no	Need better routine
2	Weekly Cl	✓	no	60%	Ops./Main	no	Unclear distribution
3	Lubricatio	no	no	75%	Maint.	no	Need schedule
4	Daily PM	✓	n/a	60%	Maint.	no	Ops. wants to do
5	Weekly or	✓	✓	60%	Maint.	yes	
6	Inspection	no	no	?	Maint.	yes	Need procedule/schedule
7	Predictive	✓	✓	50%	Engr.	yes	Maint. wants to do
a)	Estimated % of time spent on breakdown work:					80%	Reduce
b)	Estimated % of time spent on PM / PDM work:					5%	Too little
c)	Estimated % of time spent on other planned maintenanc					15%	Need more
	Total					100%	

FIGURE 16.3.10 Current maintenance assessment. (*Reprinted by permission of the International TPM Institute, Inc.*)



TPM Housekeeping Survey

Equipment Name press Equipment No. 54321 Observer Charles

Date 3 /jan / 99 Product Group B trans Location area 1

(1 is poor appearance, with 5 being excellent appearance)

	1	2	3	4	5
1. General appearance of machine	☐	☐	☑	☐	☐
2. Floor space and arrangements of work area	☐	☑	☐	☐	☐
3. Organization of cabinets and tooling	☐	☐	☑	☐	☐
4. Work area ergonomically laid out	☐	☐	☐	☑	☐
5. Lighting of work area	☐	☐	☑	☐	☐
6. Condition of other equipment, hoist, load station, etc.	☐	☑	☐	☐	☐
7. State of environment, noise, coolant mist, air quality	☐	☑	☐	☐	☐
8. Area housekeeping schedule	☑	☐	☐	☐	☐
9. Importance of housekeeping	☐	☐	☑	☐	☐
10. Safe environment	☐	☐	☐	☑	☐
11. Machine and work area overall cleanliness	☐	☐	☑	☐	☐

Comments and Suggestions:

Much clutter, area needs a thorough cleaning.
Noted no posted schedule, records, or plan for housekeeping.
Should be thoroughly cleaned, painted, and organized.

Please return this completed form to the TPM Coordinator, or committee member.

FIGURE 16.3.11 A basic housekeeping survey.

Cost Analysis

Time equipment was observed ________ 1258 minutes
Downtime noted on observation sheets ___ 189 minutes
Using observations, downtime was ______ 15%

Operation cycle speed ___________ 8.5 cycles / minute
Production lost during observations ___ 1600 parts
Cost per part ______________ $10.50 per part
Annualized losses ___________ $16,080 per year
Each 1% of downtime is worth _______ $1,072

(There are many different approaches, this is just one example)

FIGURE 16.3.12 A basic financial example—typical of early observations.

tion of differing types of manufacturing can create the need for more or less detail and different formats. We have included some of the basic examples, which should aid the discussion and offer a starting format.

Costs:	**Benefits:**
• Equipment improvement	• Better equipment productivity
• Skills training	• Productivity improvement
• TPM team meetings	• More plant capacity
• TPM training	• Higher equipment speed
• Additional PM and cleaning	• Fewer equipment repairs
• TPM staff	• Better product quality
• TPM promotion	• Reduced absenteeism

FIGURE 16.3.13 A cost-benefit analysis.

MEASURING EQUIPMENT PRODUCTIVITY

Within most plants there is hidden production capacity. Hidden losses often reach 25, 30 percent, or more. There are also ways to calculate current productivity, determine equipment potentials, and produce a fairly good measure of improvement potentials by identifying and eliminating losses, as shown in Fig. 16.3.14.

In Fig. 16.3.14, true equipment productivity is measured by total effective equipment productivity (TEEP). This overall formula includes equipment utilization (EU) and OEE. Using the TEEP formula produces the measurement for effective productivity. By knowing the level of planned equipment downtime, equipment utilization, and OEE, TEEP is then calculated.

Overall equipment effectiveness is the traditional and most widely used TPM measure. It is a reflection of equipment performance, and a precise calculation to determine how effectively equipment is being used. There are a number of details around setup and changeover time that are not specifically analyzed through OEE. OEE however is an accurate way to determine the current effectiveness of the equipment being operated.

The third formula in Fig. 16.3.14 clearly reflects the true quality and effectiveness of equipment while it is operating. Net equipment effectiveness (NEE) excludes planned downtime,

TEEP (total effective equipment productivity)

$$= \text{Utilization} \times \text{availability} \times \text{performance efficiency} \times \text{rate of quality}$$
$$= 60.4\% \times 86.2\% \times 58.0\% \times 97.9\% \times 100 = 29.6\%$$

or

$$\frac{426 \times 100}{1440} = 29.6\%$$

OEE (overall equipment effectiveness)

$$= \text{Availability} \times \text{performance efficiency} \times \text{rate of quality}$$
$$= 86.2\% \times 58.0\% \times 97.9\% \times 100 = 49.0\%$$

or

$$\frac{426 \times 100}{870} = 49.0\%$$

NEE (net equipment effectiveness)

$$= \text{Uptime} \times \text{performance efficiency} \times \text{rate of quality}$$
$$= 93.7\% \times 58\% \times 97.9\% \times 100 = 53.2\%$$

or

$$\frac{426 \times 100}{800} = 53.2\%$$

FIGURE 13.3.14 The three formulas used in TPM.

and also excludes setups and adjustments; it is thus an excellent measure of the true mechanical condition of the respective equipment.

Equipment Losses

The calculation of these three indices—TEEP, OEE, and NEE—require knowledge of equipment losses and equipment utilization. TPM focuses on equipment losses, which cut into equipment effectiveness (see Fig. 16.3.15). Equipment losses can result from:

- Setup and adjustments
- Equipment failures
- Idling and minor stoppages
- Reduced speed
- Process defects

It's not uncommon for equipment to need warm-up time, test runs, validations, and so on. These are losses to productivity that reduce product yields. They are often just ignored, or considered part of the cost of doing business. Few companies actually see them as a loss, or even attempt to minimize it. The use of OEE in these circumstances to calculate equipment performance at installation, and again after stable production has been achieved, will determine this yield loss.

The first losses, *setup and adjustments,* are not avoidable in companies where equipment needs to be set up or changed over for different products or sizes, but they can be greatly reduced. During these losses, the equipment is not broken down, but it does not produce

Equipment availability	**Setup and adjustments** Including changeovers Programming Test runs **Equipment failures** Sporadic breakdowns Chronic breakdowns
Equipment efficiency	**Idling and minor stoppages** Jams and other short stoppages No parts, no operator Blocked Many other reasons **Reduced speed** Equipment worn out Lack of accuracy Operator choice
Quality	**Process defects** Scrap Rework Others (define)

FIGURE 16.3.15 Equipment losses.

product. Since these losses are variable, they offer opportunities for reduction, which inversely provides more productive time.

Equipment failures or breakdowns (unplanned downtime) are normally another large part of equipment losses. These can be very frustrating because of their sporadic and sometimes even chronic nature. Often they represent only a minor repair, which becomes difficult to handle during a production run. Even minor problems can have catastrophic consequences when they occur during a normal production run. Some plants just accept these as unavoidable. This is a very expensive compromise that is not acceptable under a TPM implementation.

These first two losses are the components in the measurement of equipment availability. The next two losses are called hidden losses. They are rarely measured, or recorded as downtime. Maintenance personnel are not notified, and equipment is not broken—it's just being run less efficiently. *Idling and minor stoppages* fall into this category. The equipment is usually running (idling), but product is not being processed. There may be a jam or the previous or next machine may be blocked or broken down; the operator may be distracted for a few seconds. Getting materials may require operators to step away momentarily, or any number of factors can cause idling and minor stoppages. Do not underestimate the impact of these problems, especially in manufacturing plants, since they can suffer major losses because of hidden problems.

Reduced speed is the fourth major equipment loss. It often stems from poorly maintained, worn, or dirty equipment. On countless occasions, these losses remain in the production process from the initial debugging and startup phase of the equipment. Often a defective mechanism or design weakness may contribute to speed loss problems. Performance efficiency is calculated using idling and minor stoppages, and reduced speed.

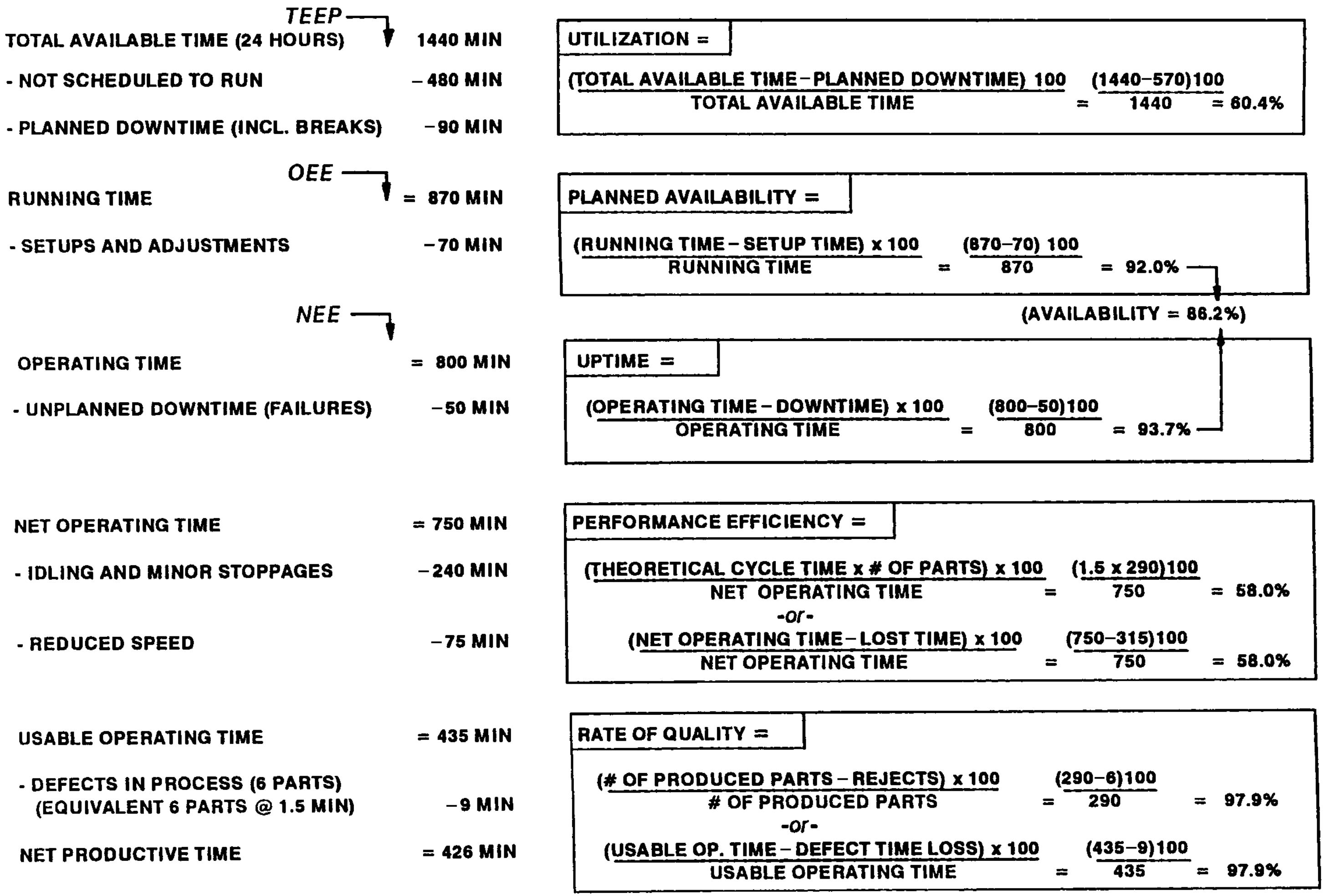

TEEP
TOTAL AVAILABLE TIME (24 HOURS) 1440 MIN
- NOT SCHEDULED TO RUN −480 MIN
- PLANNED DOWNTIME (INCL. BREAKS) −90 MIN
OEE
RUNNING TIME = 870 MIN
- SETUPS AND ADJUSTMENTS −70 MIN
NEE
OPERATING TIME = 800 MIN
- UNPLANNED DOWNTIME (FAILURES) −50 MIN
NET OPERATING TIME = 750 MIN
- IDLING AND MINOR STOPPAGES −240 MIN
- REDUCED SPEED −75 MIN
USABLE OPERATING TIME = 435 MIN
- DEFECTS IN PROCESS (6 PARTS)
(EQUIVALENT 6 PARTS @ 1.5 MIN) −9 MIN
NET PRODUCTIVE TIME = 426 MIN
UTILIZATION =
(TOTAL AVAILABLE TIME − PLANNED DOWNTIME) 100 / TOTAL AVAILABLE TIME = (1440−570)100 / 1440 = 60.4%
PLANNED AVAILABILITY =
(RUNNING TIME − SETUP TIME) x 100 / RUNNING TIME = (870−70) 100 / 870 = 92.0%
(AVAILABILITY = 86.2%)
UPTIME =
(OPERATING TIME − DOWNTIME) x 100 / OPERATING TIME = (800−50)100 / 800 = 93.7%
PERFORMANCE EFFICIENCY =
(THEORETICAL CYCLE TIME x # OF PARTS) x 100 / NET OPERATING TIME = (1.5 x 290)100 / 750 = 58.0%
-or-
(NET OPERATING TIME − LOST TIME) x 100 / NET OPERATING TIME = (750−315)100 / 750 = 58.0%
RATE OF QUALITY =
(# OF PRODUCED PARTS − REJECTS) x 100 / # OF PRODUCED PARTS = (290−6)100 / 290 = 97.9%
-or-
(USABLE OP. TIME − DEFECT TIME LOSS) x 100 / USABLE OPERATING TIME = (435−9)100 / 435 = 97.9%

FIGURE 16.3.16 Measuring equipment productivity.

The fifth equipment losses are *process defects.* Rejected parts and rework are losses related to quality. With the competitive environment of business, quality is a minimum requirement; defects caused by equipment cannot be tolerated. Through TPM, quality losses are identified, investigated, and eliminated because the rate of quality is a key element in the calculation of OEE. Through TPM, plants have the potential to find these losses, measure them, and include them in the development of real loss data.

Calculate Equipment Effectiveness

When all known losses are identified, equipment effectiveness will be calculated on a step-by-step basis. In Fig. 16.3.16, the procedure and a typical example is demonstrated. Equipment is placed in the plant 24 hours each day. Therefore, the total available minutes in a 24-hour day (1440) represents the potential production time for equipment. If a company produces products on two shifts (8 hours each), the available production time is reduced to 16 hours each day (960 minutes). Further time losses must be subtracted, such as planned downtime, meetings, lunch, breaks, or no scheduled production. The calculation in Fig. 16.3.16 will establish the percentage of equipment utilization at 60.4 percent.

When the remaining unused time is deducted, the resulting running time (870 minutes) allows the calculation of OEE. Subtracting time spent for setups, changeovers, and adjustments (70 minutes), the planned availability can be determined (92.0 percent). This is one part of equipment availability (EA).

After deducting setups and changeovers, the operating time remains (800 minutes). At this point the calculation of the net equipment effectiveness begins. By removing losses due to breakdowns (unplanned downtime), the percentage of uptime (93.7 percent) is calculated. In far too many occasions this is the number that plant management receives, creating a false impression of equipment potential and performance. This is only one loss, but management is usually conditioned to accept these uptime numbers as the measure of equipment performance. Having the equipment up and running is only part of the process elements. When equipment is analyzed against the actual time it was scheduled to operate, a significantly different percentage of performance is developed. Uptime is one key piece of information, but if the equipment is planned to be available 92 percent of the time, uptime (93.7 percent) multiplied by planned availability (92 percent) means that *equipment is really productive only 86.2 percent* of the time. Dividing the running time (870 minutes) into the remaining net operating time (750 minutes) can produce the same result.

The last calculation determines the rate of quality. This defect time is subtracted from the usable operating time resulting in the net productive time. In our example, 6 parts took 1.5 minutes each to produce; this makes an additional loss of 9 minutes (rate of quality 97.9 percent). The remaining time is 426 minutes.

Consider beginning with 24 hours in every day (1440 minutes). This has been reduced to only 426 minutes of net productive time, where good parts or product is actually produced! There are large opportunities for improvement here. The information for the examples came from a feasibility study team that concentrated on items like setups, adjustments, equipment failures, idling and minor stoppages, and speed losses. This approach offers a way to develop useful information about actual equipment condition.

Far more information and assistance are needed than was included in this section. We suggest reading additional articles or books on TPM. Visiting a TPM installation location (if possible) or attending a seminar might be useful too. The key is to research, investigate, learn, observe, and apply this key competitive concept in your plant.

CONCLUSION AND FUTURE TRENDS

Over the past two decades, TPM has helped plants the world over, whether they are from among the world's largest corporations (over 5000 employees) or small plants with 200 employees. It has benefited oil fields in Argentina, electronics plants in Mexico, automotive plants in the United States, automotive supply plants in Germany, and tire manufacturers in Portugal, Scotland, and the Czech Republic. TPM has produced a measurable impact on company's productivity, competitiveness, and quality of product and corporate culture. Many of these plants have accomplished a return on investment of over 400 percent.

Not all plants have succeeded however. There is a clear set of TPM success factors, and the absence of only one can lead to failure. The following factors are a prerequisite for TPM success:

- Top (plant) management must be trained and informed first, and must want TPM.
- The union leadership must be trained and informed at the same time, and must support TPM.
- The stakeholders (operators, maintenance, and engineering) must be informed and trained early.
- A complete TPM feasibility study must be conducted, and the result presented to management.
- A custom-made TPM installation plan (starting with pilot installations) must be developed, based on the results of the feasibility study.
- A TPM organization must be established and be permanent. The following key functions must be included: (1) the TPM manager/coordinator (who often is an industrial engineer), (2) the TPM small groups (made up of operators, maintenance personnel, and engineering support) that permanently practice TPM on their equipment, and (3) the TPM steering committee, which establishes the TPM policies and receives the project reports.
- The strong, permanent, and visible support of the plant manager, who must demand progress and results, but who also ensures that the TPM teams have time to meet and produce results.

Remember TPM is not a maintenance program. It is a holistic approach to permanently improve the function, performance, quality, and life of your equipment. How you maintain your plant equipment is paramount to accomplishing results. Therefore, with TPM, the way you maintain equipment will likely change dramatically, with operators taking on a more proactive role, in teamwork with maintenance. This in turn will change your corporate culture: teamwork throughout the plant and delegation of authority to improve and maintain equipment to the plant floor (the TPM teams). The delegation of a large degree of responsibility to the teams, continuous focus on quality and productivity by everybody in the plant, and continuous improvement of skill levels creates a pride in being part of a world-class company.

TPM is hard work and requires constant focus and support. The rewards are a competitive plant with increased productivity and lower costs, better product quality, a clean plant and work areas, and a new sense of pride and spirit throughout the whole plant.

TPM is a key competitive advantage. The need for faster production, along with technological improvements and cost control, has created an unmet need. Businesses now need more integrated systems approaches that include the final step in the process: the customer. Meeting this need, TPM makes great financial sense by providing a systematic and responsive approach to ever changing competitive pressures. In the coming decades, companies that are slow to react, that fragment operations, and who foster internal competition will be constantly overwhelmed by crisis situations. Without a dedication to the ongoing improvement of the entire business, success and even survival is at risk. TPM teaches us how to succeed by breaking wasteful practices while using the experts we already have—our people.

During the last few decades of manufacturing, we've witnessed failures of some major corporations. They often failed to recognize the paralysis and devastation caused by measuring performance only at the departmental level. Freezing performance into preconceived outlines of success turns a blind eye to the dynamic nature of the real world. We can't afford to violate any of the success factors, but, when they're violated, often the justification is that the organization was attempting to do what was best, or to practice good management. Doing the very best and losing the business at the same time, how could that happen? TPM breaks this failure mode, focusing on the largest single corporate asset—its equipment—while improving productivity, quality, competitiveness, and the corporate culture—all accomplished through teamwork.

In the future, successful companies will be recognized by the way they measure progress. Their perspective will be from the corporate whole with groups rewarded for collective achievements. TPM is useful for these companies; it recognizes the collective strength of organizations when sharing a common objective. It's a foundational concept that will protect the assets for the investor and improve the competitiveness of the enterprise, while moving the entire business forward. TPM, successfully installed, is a key competitive and financial advantage.

FURTHER READING

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BIOGRAPHIES

Edward H. Hartmann is the founder and president/CEO of International TPM Institute, Inc. He was born in Switzerland and grew up in Zurich. After receiving his mechanical engineering degree, he emigrated to Canada and came to the United States in 1964. He studied industrial engineering at McGill University in Montreal and at the University of Southern California. Positions held in his early career were design engineer, industrial engineer, and manufacturing engineer. He is a registered professional engineer (P.E.) in the state of California. In 1969, he joined an international management consulting firm and eventually became a senior vice president, member of the board of directors, and president of its training division. Since 1986, he has studied the application and results of TPM during numerous plant visits to Japan, and in 1987 formally introduced TPM to American industry at a TPM executive conference in Pittsburgh. Since that time, Hartmann has trained over 8000 managers, engineers, and other personnel in TPM.

Herbert L. Charles began his maintenance career at General Motors (GM) in 1967. He served a four-year apprenticeship to become a Skilled Trades Journeyman. In 1985, he was appointed cochairman of a Planned Maintenance Strategy Committee for the GM Quality Network. Charles holds a bachelor's (B.S.B.A.) and a master's degree in business administration (M.B.A.) from La Salle University. He joined GM's Saturn Division in 1989 where he was the maintenance and TPM coordinator for eight years. After leaving Saturn in 1997, he became a senior TPM consultant for the International TPM Institute, Inc. Charles is presently the corporate operations maintenance manager for Haworth, Inc., a multinational furniture manufacturer.

CHAPTER 16.4

CASE STUDY: AUTOMATED JOB STANDARDS FOR AIRCRAFT MAINTENANCE

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British Airways Engineering recently conducted a project to build a database of engineered labor standards for aircraft heavy maintenance activities on their entire fleet of jet aircraft. This project was motivated by the lack of consistent and accurate standards in the existing system. British Airways thoroughly researched all available options prior to moving forward with the project. The Man-Hour Matrix (MANX) Project used predetermined motion time systems, standard data, computerized work measurement, and expert system technology to create an automated system for standards development and maintenance. The approach ensured that all production engineers would use the same technical approach and the same database of standard times, resulting in consistent and accurate standards across all fleets.

BACKGROUND

Motivation

In 1993, British Airways Engineering considered a potential need for the introduction of time standards for its aircraft maintenance tasks. British Airways was operating a fleet of some 250 aircraft, a mixture of Boeing, McDonnell Douglas, British Aerospace, and Airbus equipment. At that time, this number of aircraft involved represented some 90,000 work tasks, steadily increasing.

Time standards were being generated by engineers as they created job plans for maintenance. The engineers would break the jobs down into a series of tasks and estimate the time for each task. The tasks and times were then printed on job cards, which job planners used to plan and schedule the work in conjunction with the other jobs that were to be completed as part of a given service check. The problem with this approach was that the breakdown of tasks for each job, and times assigned to each task, were based on the knowledge and experience of the engineer creating the task, leading to inconsistencies in the structure of the breakdown and the associated times.

An example of this problem would be the removal of a component from within the structure of the aircraft. This task may include the disconnection and removal of that component, the removal of any necessary panels, pipes, or cables, and the reading and production of all necessary paperwork and clearance certificates. Each engineer might choose to include some or all of these steps as a part of the job, with assigned time for each based on personal experience.

These variations in methods could cause a variance in positive or negative database times for the task by several hundred percent, making downtime scheduling and maintenance costs difficult to control.

If this is looked at in the context of the British Airways fleet, accurate planning is difficult both from the hangar and the loading point of view, but planning can be managed on relatively short notice by delaying the arriving aircraft or having the ability to reschedule aircraft.

Contracting work, both internally and externally, produces a double-edged effect. If you provide a quotation of labor-hours for carrying out work for other airline customers, the quotation can become a discussion point to “talk up” the hours if the time scales are overrun. On the other hand, this can act in your favor when talking hours down, with contract companies performing work on your behalf. Time standards had to be created in a logical, traceable manner, and must stand up to scrutiny.

To improve systems, maintain leadership within the industry, and move quickly to becoming a world-class organization, a new approach was required. The MANX Project (Man-Hour Matrix) was conceived.

Technical Approach

British Airways required a system that had a proven history, as well as an existing large, credible database that could be quickly validated, and was offered by a company that would provide full training and subsequent practical and technical support and backup. It was known that no other aircraft maintenance organization had embarked on and concluded such a project as was required by British Airways Engineering. Therefore, they needed a system that would allow them to tailor it to their requirements with a minimum of effort.

Also to be considered was a potential need for the system to integrate, or relate, to the existing and/or future British Airways Engineering systems. The selected system would have to show considerable savings in the labor cost of deriving consistent standards, compared to those of traditional methods of work/time study. The system would also have to provide an “open book” approach to both technical and craft personnel alike, to give the necessary confidence to the validity of the generated data and standards.

Analysis of Alternatives

The general process for the selection of the company and system involved a review of the total marketplace, including information such as company sales literature. From this information, a short list of prospective systems was established. (For commercial reasons, the companies, the databases they offered, and details of specific criteria cannot be discussed in this study.) A detailed analysis of a number of typical aircraft maintenance tasks was generated and passed to the prospective suppliers so that they could apply their system to generate time standards against the tasks, along with a standard questionnaire and a draft of the technical/functional specifications.

A systematic decision analysis (Kepler Trager) based on the preceding information and subsequent results was carried out, including crucial criteria such as consistency, speed and ease of use, accuracy of generated data, cost, and time scales that provided the best value. H. B. Maynard and Company, Inc., and their MOST® work measurement system was selected.

Decision to Move Forward

Having decided which system and company would best meet British Airway's needs and objectives, the process of setting up a dedicated project team began.

The team was to comprise a project manager and four staff: a project engineer, a production engineer, a licensed aircraft engineer, and an aircraft technician, one of whom would be a trade union–nominated representative. To supplement this team, a MANX Champion was nominated from each of the fleet production engineering groups to work closely with the project team and to represent the perspective of the eventual end users of the system. Good industrial relations were clearly a success criteria, with the trade union's support essential to the short time scales for the project.

It would be the project team's responsibility to become fully trained in the work measurement tools and techniques. From that point on, the team would be responsible for managing the project, developing the system, deriving the data, and implementing a training program that would introduce both the production engineers and their support staff to the use of the new system.

It was also essential that the project team take responsibility for communicating plans and new developments to all staff affected by the implementation of the system, from fleet general managers to the aircraft technicians and licensed aircraft engineers.

THE MANX PROJECT

Standard Data Development

Aircraft heavy maintenance work encompasses a dizzying number of jobs. The challenge for the project team was to find a way to measure all this work in a relatively short amount of time. In response, the team chose to develop standard data using the Top-Down data development technique.

By first considering all work that needed to be measured, and identifying the common elements that exist in many jobs, the team was able to create a simple element list before any measurement was done. This list of several hundred basic work elements allowed them to be certain that each basic task, or suboperation, was measured only once.

Once the list was complete, MaxiMOST® was used to measure the work. MaxiMOST is a member of the MOST family of predetermined motion time systems, designed especially for measuring long-cycle, nonrepetitive operations like maintenance.

Throughout the data development process, the team interacted with the hangar floor and maintenance training personnel. This allowed the team to clearly identify the approved best methods and practices used to complete a variety of tasks. This approach also helped the project to establish credibility with the workforce.

The data was created and stored in a database using MOST for Windows and MOST Data Manager software. With this relatively small database of a few hundred standard data suboperations, the team was able to provide standards coverage for a large majority of the heavy maintenance work.

Aircraft Maintenance Task Oriented Support System Breakdown

To create a structured system, a means of logically and systematically filing data had to be derived. The Civil Airline Industry, over the years, has structured itself in line with the Air Transport Association of America (ATA). To try to explain all the agreed to systems within the ATA in this study would not be appropriate, but suffice to say several forms of data identification have been developed. Each defined section of an aircraft is identified by a chapter number (ATA chapter): engines, Chap. 72; autoflight, Chap. 22; air conditioning, Chap. 21; and so on. This identification applies to all aircraft and aircraft manufacturers around the world, thus eliminating any confusion between manufacturers, operators, or maintenance organizations—a single language across the world irrespective of the dialogue.

In more modern aircraft, Aircraft Maintenance Task Oriented Support System (AMTOSS) coding is extended down to every individual maintenance task performed on the aircraft by the use of increasing blocks of numbers. Part of this coding identifies the function of such tasks:

00 Removal   10 Clean   20 Inspect
30 Repair   40 Install   70 Test

These codes and headings were designated as two of the key data filing/retrieving fields when generating elemental level data, allowing for simple search and retrieval procedures.

Other search fields included

- *Activity:* attach, move, read, setup, drill
- *Object:* fastener, lubricant, paint
- *Product/Equipment:* air gun, power tool, test equipment
- *Tool:* hand tool, brush, screwdriver

Accessibility Issues

The sub operation times generated depend, in general, on the aircraft engineers having good access to the job being worked on. In the aircraft maintenance business, this tends to be the exception rather than the rule. In many cases, the degree of difficulty of access to a single component will vary from direct to extremely difficult due to its location and surroundings.

To assess the effect of these variations, a series of work sampling studies on a number of specific tasks was carried out. An identical task was carried out and timed for a number of engineers across three aircraft types, with each task having four levels of difficulty, for example, removal of a split pin and nut in five locations with four levels of difficulty.

The levels of difficulties include

- Direct visual and tactile access
- Direct visual but restricted tactile access
- Restricted visual but direct tactile access
- Restricted visual and tactile access

The results, when statistically analyzed, showed that only three levels of difficulty existed. An allowance factor, based on the work sampling method and applied as a percentage, was developed for each of these three levels.

Because the degree of difficulty may not have been readily apparent to the production engineer when creating the standard, and the task involved various access levels, it was agreed that all standards, when created, would be based on easy access. For jobs where it was subsequently shown that this was obviously incorrect, a review would take place and an appropriate allowance added.

Data Application

The next challenge was to provide the production engineers with a means for selecting the proper standard data for each job. Even though the database was relatively small and the search criteria quickly narrowed the choices, an automated system was required to allow production engineers to establish standards quickly and in a consistent format.

The AutoMOST system was chosen to automate the data application process. AutoMOST® which was a development tool the team used to build an expert system for establishing labor standards. The result was a system that would guide the production engineer through a structured series of questions. Based on the engineer's response, the system would automatically select the data and apply the appropriate frequencies. The system would then ask the next logical question until the job was complete.

To develop such a tool, the team had to reach a consensus on the proper steps and sequence for completing any given job. The team was also challenged by the nature of maintenance work whereby almost any number of additional jobs might be required in order to complete the original task.

In response to these challenges, the team developed a series of job models on which the system was based. The team identified five possible kinds of aircraft heavy maintenance work: component installation/removal, function test, replenishment, inspection, and repair.

General Structure of Jobs for Specific Job Types

Job standards are built in a modular fashion, utilizing the standard data. The general job structure is outlined by a series of levels (see Fig. 16.4.1).

At the lowest (first) level, we have *suboperations,* which are the lowest measurable units of work, such as remove a threaded fastener, and these are measured using the MaxiMOST technique. This was the first data developed at British Airways (BA), including over 300 suboperations.

The intermediate (second) level of data is known as *standard operations,* and is derived by building suboperations into combinations that can be used by the production engineer to build a job standard.

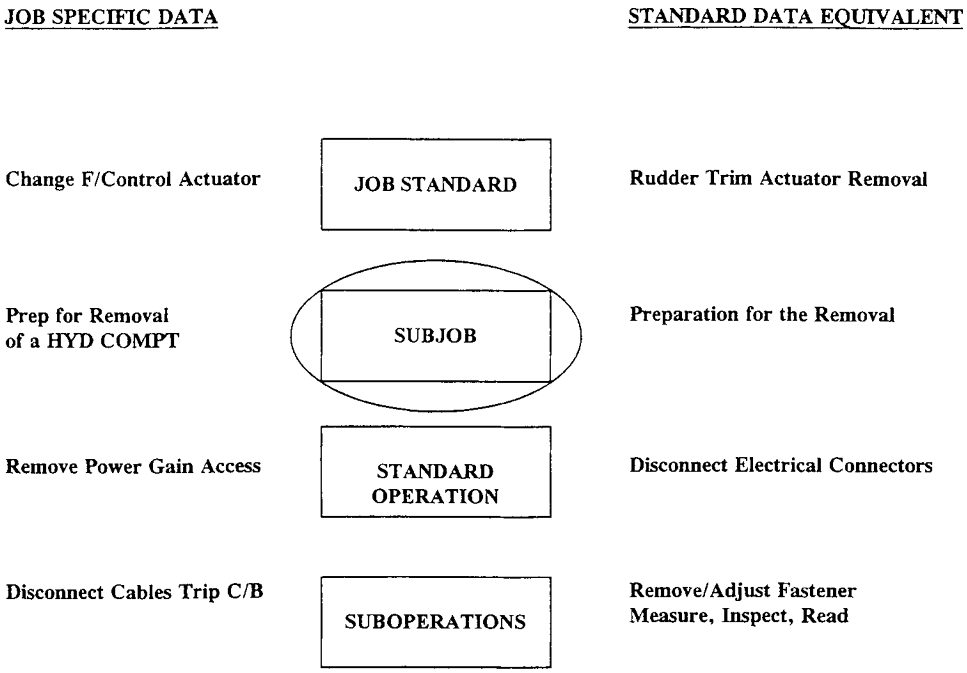
JOB SPECIFIC DATA
STANDARD DATA EQUIVALENT
Change F/Control Actuator
JOB STANDARD
Rudder Trim Actuator Removal
Prep for Removal of a HYD COMPT
SUBJOB
Preparation for the Removal
Remove Power Gain Access
STANDARD OPERATION
Disconnect Electrical Connectors
Disconnect Cables Trip C/B
SUBOPERATIONS
Remove/Adjust Fastener Measure, Inspect, Read

FIGURE 16.4.1 Job system—general structure.

The highest (fourth) level in the system will be *job standards,* which will be broken down into subjob blocks (third level) depending on the job type.

Job Models

The job model is an outline of the basic tasks that constitute an entire job. Use of the models allows the team to build a consistent job structure into the expert system. This consistent structure will serve to guide all production engineers through the process in a similar fashion. This definition also helps to ensure that no part of the task will be omitted.

These models were developed through extensive consultation with production engineers and managers. This ensured that the models, as developed, reflected the accepted standard approach of production engineering as a whole. A typical job model for the component installation/removal is shown in Fig. 16.4.2.

The model is a simple and straightforward guide that will apply to any component removal or installation. This type of rigid structure is required in this industry. Aircraft maintenance is

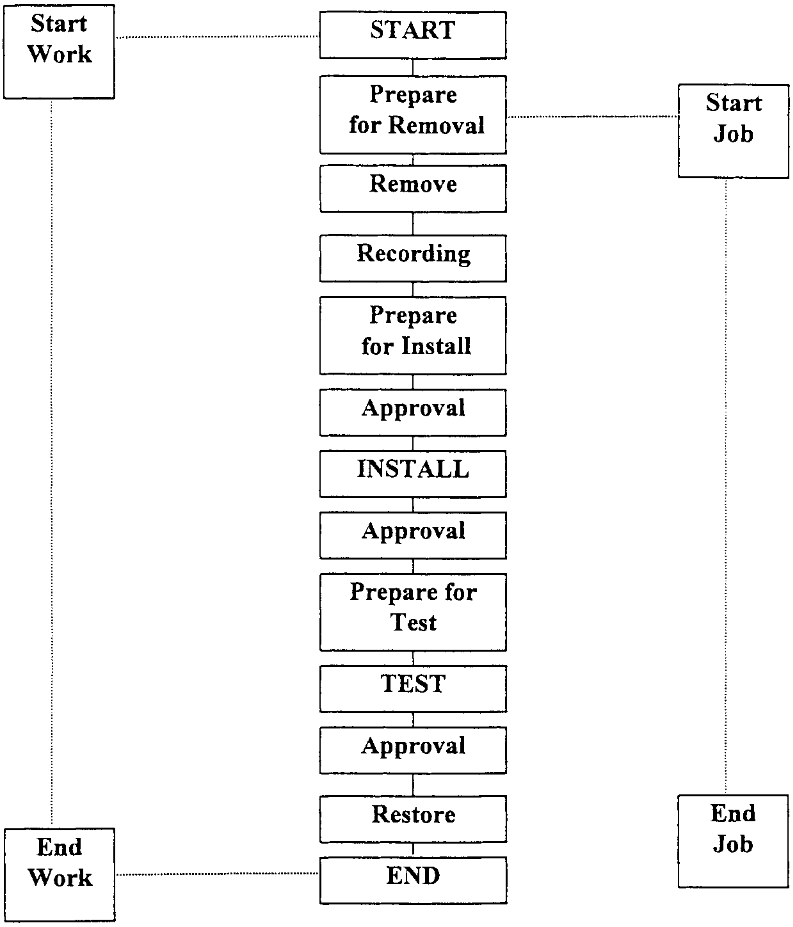
Start Work
START
Prepare for Removal
Start Job
Remove
Recording
Prepare for Install
Approval
INSTALL
Approval
Prepare for Test
TEST
Approval
Restore
End Job
End Work
END

FIGURE 16.4.2 Component remove/install process.

CASE STUDY: AUTOMATED JOB STANDARDS FOR AIRCRAFT MAINTENANCE

highly regulated by authorities with extreme executive powers, even to the extent of withdrawing an organization's approval to operate. Within the organization, authority granted by regulating authorities is complex, with signatory powers of the individuals being limited at different levels. Every task carried out becomes accountable to the authorized individual.

At first glance, the job model in Fig. 16.4.2 appears to have more than one START and END, but START and END are each subdivided into two activities. The following discussion examines the job model tasks in more detail.

Start Work commences at the point the mechanic or technician is allocated the task or job, but does not yet allow him or her to touch the aircraft—this is the point at which the regulations begin. Work on the aircraft must not proceed until the tasks have been fully identified; the mechanic or technicians sign onto the job for traceability purposes, and the manuals relating to the task are verified for compliance, read, and understood. Special approved tools and equipment may be required and replacement parts withdrawn from the bonded store.

Start Job is where the mechanic or technician carries out the first part of the task, which would render the aircraft unfit to fly should the task be carried out in isolation.

Prepare for Removal allows for such tasks as making the aircraft safe for task, removing electrical or hydraulic power, installing necessary mechanical locks, performing necessary safety checks, and removing panels that allow access to the component being removed.

Remove is the act of actually removing the component. This step is deemed to begin at the first action that will render the component unserviceable (e.g., disconnecting electrical plugs, linkages, and fasteners).

Recording is a regulatory requirement where the component part number and serial number are recorded in the aircraft history.

Prepare for Install incorporates the requirements necessary before the replacement component may be fitted to the aircraft. It will include the inspection of the supplied component to ensure correctness in terms of part/serial numbers, modification status, visual inspection for component integrity, removal of any transportation guards and blanks, and where necessary, attachment of installation tooling.

Approval has to be given by an authorized person to allow the physical fitting of the unit to the aircraft.

Install occurs when the unit is positioned and connected to the aircraft. All cables, plugs, linkages, and so on are connected. Where necessary, the component or attached items are configured and any installation tooling removed.

Approval is conducted by an authorized member of the team who inspects the work carried out to the requirements of the maintenance document, records the part/serial number, and signs for the installation.

Prepare for Test will require the component to be made ready for a functional test and may include the attachment of test equipment and possible reenergizing of the aircraft's electrical and hydraulic systems, with all the accompanying safety requirements.

Test will include the functioning of the component and the system to which it is part of, and may also include any required adjustments to allow function to specification.

Approval is granted when the satisfactory conclusion of the testing is recorded in the aircraft records and again signed for by an authorized person.

Restore the aircraft back to operational conditions. This will include removal of any test equipment, returning power systems to their required condition, and repaneling where necessary.

End is not the point at which the mechanic or technician walks away from the aircraft with the knowledge that he or she has once more made the aircraft safe to fly. The final paper-

> work has to be completed, tools returned, equipment taken to stores, and the removed component routed to stores or the repair shop. Finally, to be satisfied, think, "They fixed it and they will be happy to fly in it."

This gives you some insight into the high cost of maintenance. All the job model tasks must be considered, even for minor changes, such as a single gauge in the cockpit or even a failed seat back video screen. For all maintenance tasks, this entire structured procedure must be followed.

Expert System Development

The job models for each of the areas—component installation/removal, function test, replenishment, inspection, and repair—were used as a guide to develop the automated procedure using the AutoMOST system. Based on the type of job, the system was built to prompt the engineer with specific questions about the characteristics of the job.

A major challenge faced by the team was related to the infinite number of combinations of job types that could happen. For example, during any given component installation, an entire function test might be required. Within that function test, an inspection might be required, and so on.

This led the team to develop the expert system so that the engineer had the option to jump from the middle of one job model to the beginning of another at any time. The system would keep track of the engineer's progress through each model, and be certain that all required tasks were accounted for before jumping back to the previous model.

As a result, the expert system provided significant benefits. Foremost, the system provided a consistent, structured approach that yielded similar results for all production engineers. The standard data database, which supported the expert system, ensured that the resulting job time would be accurate and consistent. Yet, despite the consistency, the system was flexible enough to handle any heavy maintenance task, simple or complex.

The MANX team developed a course for production engineers. The course began by demonstrating the importance and significance of the data, which supported the MANX system. This was an important step because it helped to build credibility and acceptance of the system. The course concluded by walking the engineers through several examples so they could see how they would use the system to create new job standards.

Systems Integration

After the expert system completed a job standard, all relevant data relating to times and methods were stored in a relational database. A transfer program was designed by the systems team to export all necessary data from the MANX system to OMEGA, which is a maintenance planning system that gathers all time, methods, tooling, materials, and safety information into a single job plan. This job plan was delivered to the maintenance planners, who were responsible for planning and scheduling work on the hangar floor.

Each job plan includes a set of job cards. The job cards allow the individuals who are responsible for completing the work to see the job standard for each job and understand the expectations prior to beginning the work.

RESULTS

The resulting system guides engineers through the process of establishing accurate and consistent standards in a relatively short period of time. The project team validated the standard times through hangar floor observation and comparison to actual job times.

One of the most significant benefits of the MANX system was that it eliminated many of the inconsistencies that were part of the old estimating system. MANX ensured that engineers responsible for creating standards for similar jobs on different fleets of aircraft, where the same methods were employed, were producing consistent standards. MANX would automatically recognize and account for the variables associated with conditions such as smaller or larger aircraft, more or less modern test systems, and so forth.

British Airways Engineering's business process reengineering program has caused the full implementation of the MANX system to be put on hold at this time. A decision will be made at a later date regarding the continued implementation of MANX. Regardless, the knowledge gained and thought processes learned from the development of the project continue to benefit British Airways.

ACKNOWLEDGMENTS

On behalf of British Airways Engineering, we thank Mike Crocker and his colleagues at the Long Island Lighting Company for their time and help in the communication process, especially with trade union colleagues and senior managers.

BIOGRAPHIES

John Minnich is business development manager and shareholder in H. B. Maynard and Company, Inc. He is responsible for the sale and delivery of Maynard consulting assignments. Over the past 10 years, he has worked with clients in fabrication, assembly, metalworking, service, retail, and process industries. He has extensive experience in the application of incentives, specifically in working with clients to determine the feasibility of incentive plans, designing custom plans, developing supporting data and systems, and implementing incentive plans. He has assisted clients in capitalizing on their incentive systems to realize dramatic improvements in productivity and reductions in cost. He has been an integral part in the development and delivery of LeanLine™ Solutions to assist clients in reducing inventory and setup and response time, implementing 5S, and eliminating waste. Minnich holds a B.S. in industrial engineering and operations research from Virginia Polytechnic Institute and State University.

David Moore is a component technical engineer, supply chain, with British Airways London. He has spent the last 10 years with British Airways working in various divisions such as engineering, engine overhaul, aircraft maintenance, and central supply chain. Moore began his career as a technical apprentice with Rolls-Royce as an aircraft engine fitter/tester, working primarily with helicopter engines. He also spent 13 years as a test facility project engineer overseeing design, procurement, assembly, and commissioning of component and engine test facilities for civil and military use.

SECTION 17

TOOLS, TECHNIQUES, AND SYSTEMS

Source: MAYNARD'S INDUSTRIAL ENGINEERING HANDBOOK

CHAPTER 17.1

CHARTING TECHNIQUES

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This chapter details the procedures for creating charts and diagrams used to portray and analyze work processes or work cycles. For clarity in referring to particular types of these representational aids, we distinguish between diagrams and charts. Diagrams typically portray the physical space traversed by the object being analyzed. Charts are symbolic representations that portray activity elements in processes or work cycles. In both cases these aids are useful as communication devices, which, in addition to representing a process, lend themselves to analyses that support methods improvements. Charts and diagrams are used in process design, facility design, and in process or facility redesign. They are also very useful as training aids.

DIAGRAMS

The most beneficial tools used during either the initial stage of design or in the analysis of an existing process or a facility are those that provide a visual representation of the whole system or subsystem under study. In general, the diagrammatic representations take the form of *flow process diagrams* or *link diagrams.* In both cases, there is an "overhead" or plan view schematic representation of the process with lines tracing the flow of the object of interest.

Flow Diagrams

In the case of a flow diagram (see Fig. 17.1.1), the object being diagrammed could be material, people, lift trucks, piece parts, subassemblies, and the like—the objective is to portray the flow and relationships among activities in physical space.

Constructing a Flow Diagram

1. Observe the system of interest, recording the movements and operations performed.
2. Obtain or construct a plan or overhead view of the area occupied by the system of interest. Note N/S/E/W orientation, factory column numbers, and any other cues that will assist the observer in relating the diagram to the actual space. (The diagram need not be to scale, but it is more useful if it is.)

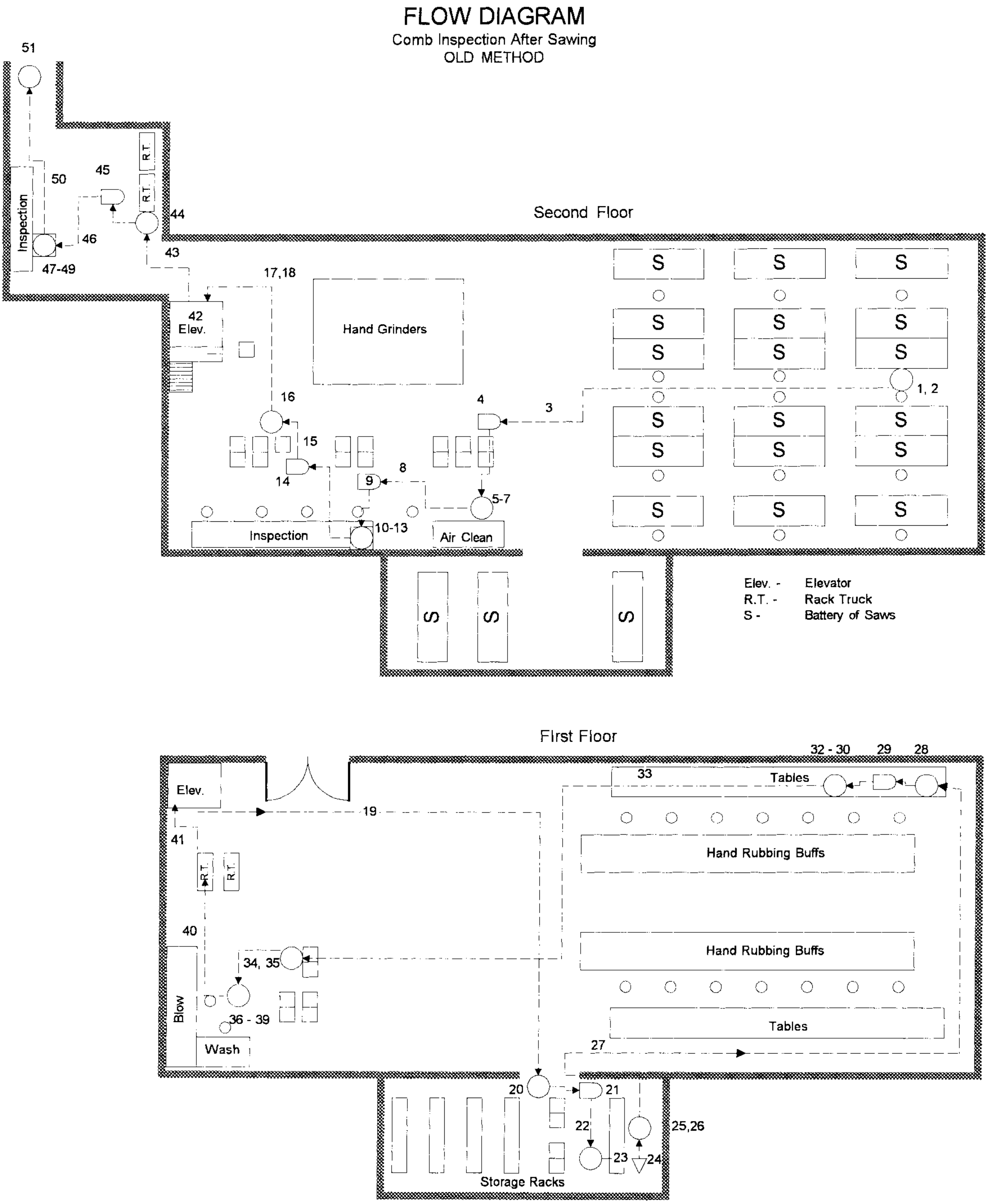

FLOW DIAGRAM
Comb Inspection After Sawing
OLD METHOD
Second Floor
51
50
45
44
43
46
47-49
Inspection
R.T.
R.T.
17,18
42
Elev.
Hand Grinders
S
1, 2
3
4
5-7
8
9
10-13
14
15
16
Inspection
Air Clean
Elev. - Elevator
R.T. - Rack Truck
S - Battery of Saws
First Floor
Elev.
19
41
R.T.
R.T.
40
34, 35
36 - 39
Blow
Wash
32 - 30
29
28
33
Tables
Hand Rubbing Buffs
Hand Rubbing Buffs
Tables
27
20
21
22
23
24
25,26
Storage Racks

FIGURE 17.1.1 Flow diagram.

3. If an item of equipment is fixed in its location due to flooring or bed requirements, access to water, pneumatics, and so on, be sure to note that on the diagram since one of the improvement methodologies is to relocate work areas.
4. Trace the path of movement of the object being analyzed onto the diagram, using arrows to indicate direction of movement.
5. Record distances traversed.
6. Prepare a succinct narrative explaining the portrayal and highlighting the problems revealed.

Analyzing a Flow Diagram

1. Analyze the flow for inefficiencies, unnecessary distances traversed, retracing of movements, and complex or illogical sequences of operations.
2. As criteria for improved flow, minimize total distance traveled, minimize the amount of backtracking and crossing paths, and minimize total time related to object flow patterns.

Link Diagrams

Link diagrams originated in the field of human factors engineering rather than industrial engineering. As illustrated in Fig. 17.1.2, link diagrams quantify connections or linkages among various equipment items and movements or linkages between the one or more persons staffing the system, and between operators and the items of equipment or machines that they use. This quantification is based on a specified period of operation to ensure that all data are comparable.

Constructing a Link Diagram

1. Observe the system of interest for a predetermined representative period of time. Record or estimate the frequency with which the human operators interact with various items of equipment and the direction of movement from machine to machine and the distances involved.

   Note. Although frequency of use is the primary metric used in link diagrams, we recommend that the analyst also highlight very important linkages, some of which may occur infrequently or may not even be observed during the period of analysis (e.g., alarms or fire extinguishers).
2. Note N/S/E/W orientation and factory column numbers. (The diagram need not be to scale, but it is more useful if it is.)
3. If an item of equipment is fixed in its location due to floor or bed requirements, access to water, pneumatics, and so forth, be sure to note that on the diagram.
4. Portray the linkages (lines of movement) to accomplish required interactions between the operator(s) and the various items of equipment and the frequency of such interactions.
5. Prepare a succinct narrative explaining the portrayal and highlighting the problems revealed.

Analyzing a Link Diagram. Analyze the portrayal with the primary objective of clustering or regrouping the equipment to shorten the travel distances and by appropriate reduction of the number of crossing links. Redesign typically starts by placing elements with the most frequent and critical links in closest proximity. Once those equipment items are located, the others are located accordingly.

CHARTS

Like diagrams, charts are also graphical representations of a system. The usual difference between a diagram and a chart is that charts portray the elements of the process in chronological relationship or process sequence, whereas diagrams portray spatial order.

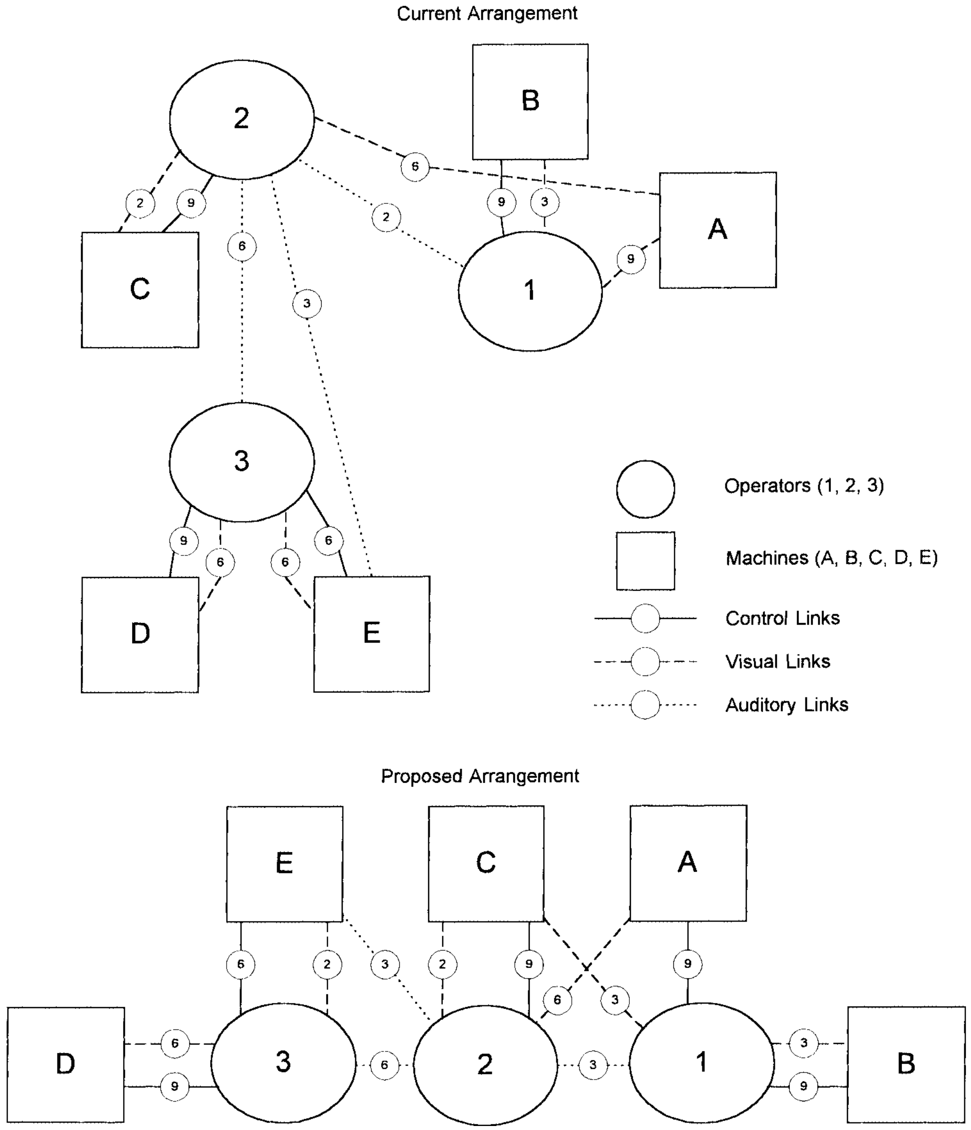

Current Arrangement
2
B
A
C
1
3
D
E
6
9
3
2
9
2
6
3
9
6
6
6
Operators (1, 2, 3)
Machines (A, B, C, D, E)
Control Links
Visual Links
Auditory Links
Proposed Arrangement
E
C
A
D
3
2
1
B
6
2
3
2
9
9
6
3
6
9
6
3
3
9

FIGURE 17.1.2 Link diagram.

Flow Process Charts

The most universally recognized and widely used form of process representation is the flow process chart. The chart captures the sequence in which activity elements take place.

Activities Defined. The activity elements are coded using five widely recognized symbols, which have been standardized by the American Society of Manufacturing Engineers (ASME). The symbols, with their definitions, appear in Fig. 17.1.3. Where there are combined activity elements (e.g., a paint-drying conveyor belt would combine an operation and a move), the symbols should be superimposed.

CHARTING TECHNIQUES

SYMBOL	ACTIVITY	DEFINITION
○	Operation	When something is done to or by the subject being followed at a given work area. Something is being changed, added to or created.
⇨	Transportation	When something is moving or being moved from one workspace or location to another.
□	Inspection	When something is checked or verified for quality or examined for information, or the act of doing so.
D	Delay	When something or someone waits or is delayed or when flow is interrupted.
▽	Storage	When something is kept and protected against unauthorized removal.
⧇	Combined Activity	When, for example, an operation and an inspection occur simultaneously.

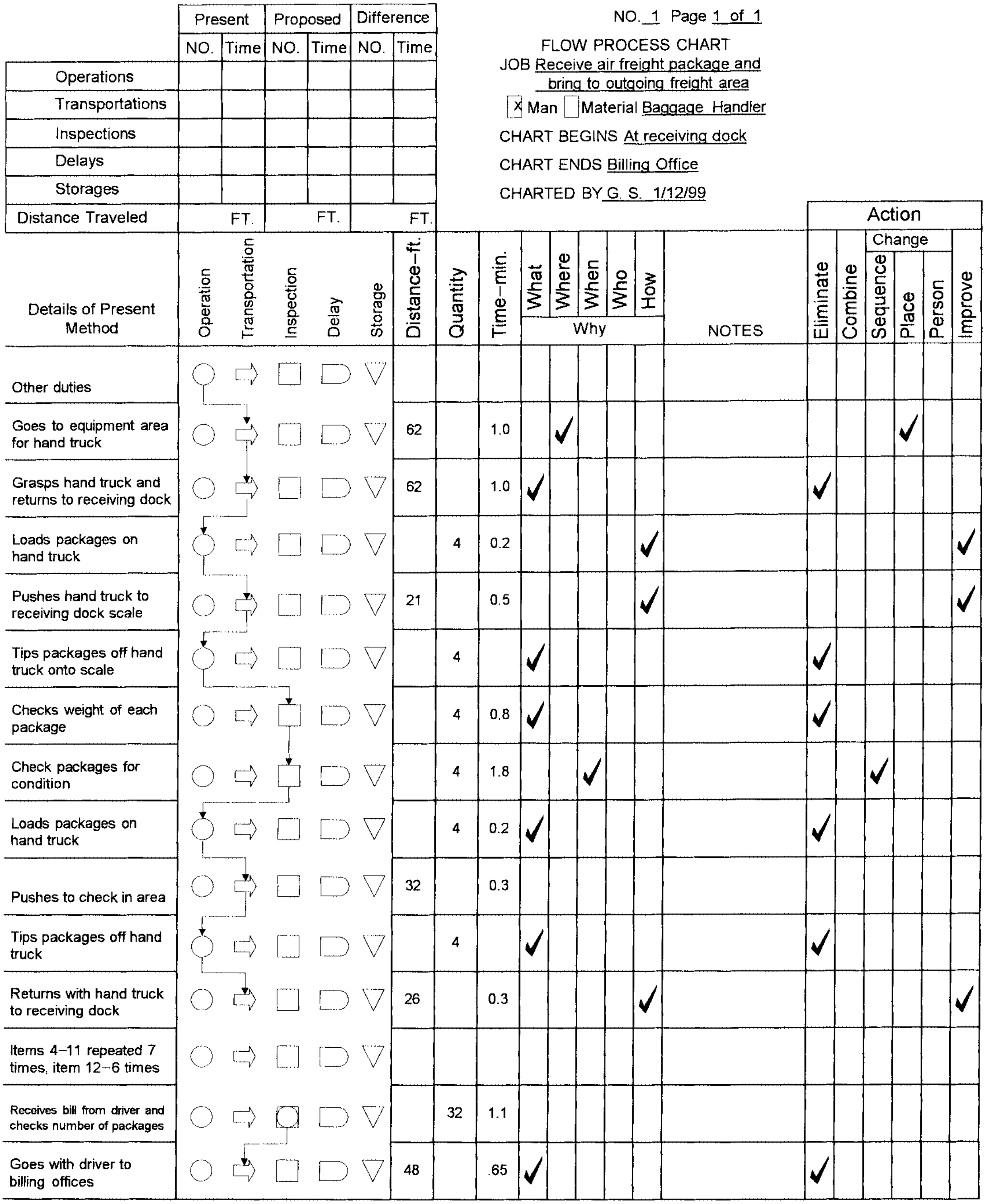
FIGURE 17.1.3 Flow process chart symbols.

It is common to use a form with preprinted symbols that eliminates the non-value-adding activity of the analyst while preparing the chart. (Figure 17.1.4 is an example of a preprinted form.) The information required to create the flow process chart typically matches the information used for a flow diagram, so the two are often created at the same time.

Constructing a Flow Process Chart

1. Observe the process of interest, or conceptualize the desired process.
2. Record the operations that make up the process of interest and record or estimate a representative time.

   Note. One error frequently committed by analysts preparing flow process charts is the transfer of the object of analysis. For example, when charting the process of loading refrigerators into trailer trucks, the analyst might chart the movement of the refrigerator from storage to a roller conveyor, the movement of the refrigerator along the conveyor, and then chart multiple trips by a forklift from the conveyor into the truck. In this example the object of analysis was shifted from the refrigerator to the lift truck. To reduce the possibility of such a transfer of focus, we recommend that the flowchart be labeled to indicate the object of the analysis, for example, Flow Process Chart—Operator Analysis, Flow Process Chart—Product Analysis, or Flow Process Chart—Information Analysis.
3. Record the distances between successive operations.
4. Prepare a succinct narrative explaining the portrayal and highlighting the problems revealed.



	Present NO.	Present Time	Proposed NO.	Proposed Time	Difference NO.	Difference Time
Operations						
Transportations						
Inspections						
Delays						
Storages						
Distance Traveled	FT.		FT.		FT.	

NO. 1 Page 1 of 1

FLOW PROCESS CHART

JOB Receive air freight package and bring to outgoing freight area

☒ Man ☐ Material Baggage Handler

CHART BEGINS At receiving dock

CHART ENDS Billing Office

CHARTED BY G. S. 1/12/99

Details of Present Method	Operation	Transportation	Inspection	Delay	Storage	Distance–ft.	Quantity	Time–min.	Why: What	Why: Where	Why: When	Why: Who	Why: How	NOTES	Action: Eliminate	Action: Combine	Action: Change: Sequence	Action: Change: Place	Action: Change: Person	Action: Improve
Other duties	**○**	⇨	□	D	▽															
Goes to equipment area for hand truck	○	**⇨**	□	D	▽	62		1.0		✓								✓		
Grasps hand truck and returns to receiving dock	○	**⇨**	□	D	▽	62		1.0	✓						✓					
Loads packages on hand truck	**○**	⇨	□	D	▽		4	0.2					✓							✓
Pushes hand truck to receiving dock scale	○	**⇨**	□	D	▽	21		0.5					✓							✓
Tips packages off hand truck onto scale	**○**	⇨	□	D	▽		4		✓						✓					
Checks weight of each package	○	⇨	**□**	D	▽		4	0.8	✓						✓					
Check packages for condition	○	⇨	**□**	D	▽		4	1.8			✓						✓			
Loads packages on hand truck	**○**	⇨	□	D	▽		4	0.2	✓						✓					
Pushes to check in area	○	**⇨**	□	D	▽	32		0.3												
Tips packages off hand truck	**○**	⇨	□	D	▽		4		✓						✓					
Returns with hand truck to receiving dock	○	**⇨**	□	D	▽	26		0.3					✓							✓
Items 4–11 repeated 7 times, item 12–6 times	○	⇨	□	D	▽															
Receives bill from driver and checks number of packages	○	⇨	**□**	D	▽		32	1.1												
Goes with driver to billing offices	○	**⇨**	□	D	▽	48		.65	✓						✓					

FIGURE 17.1.4 Flow process chart—operator analysis.

Analyzing a Flow Process Chart. Once the existing process has been charted, the analyst should undertake a systematic exploration of all aspects of the process. The techniques and methodology for such an intervention are a technology unto themselves.

Variations of Flow Process Charts

There are a large number of variations on the basic process chart, depending on the needs or objectives of the analyst. For example, flow process charts typically portray a single process. When portrayal of multiple interacting processes is required, it sometimes pays to reduce the complexity of the portrayal while expanding the coverage. An excellent example of such a variation is the operation process chart.

Operation Process Charts

Operation process charts are most often used to display multiple processes that combine to produce a complex end product. To reduce complexity and enhance the capacity of the chart to capture the whole process, usually only operations and inspections are portrayed. Since multiple processes invite a large number of alternative representations, a convention is necessary to assist the analyst in creating the chart. General practice is to begin with the part to which all other parts (manufactured or purchased) are assembled. This unit is portrayed on the far right-hand side of the operation process chart. The analyst "disassembles" the object being charted. The unit or subassembly that can be removed first is portrayed on the far left side of the chart. The remaining parts or subassemblies feed into the base assembly in the appropriate order.

Constructing an Operation Process Chart

1. Select the assembly that will be the object of the analysis.
2. Identify the part or subassembly that is the base or body to which all other parts or subassemblies are fitted. Plan to chart that unit—on the far right-hand side of the page.
3. Disassemble the final assembly.
4. Chart the unit or subassembly that can be removed first on the left-hand side of the page.

Note. Typically every part or subassembly will begin with a purchased material or item that will then be modified in a preassemble process, or assembled as purchased.

5. Continue charting from left to right until the entire assembly is portrayed. (See Fig. 17.1.5 for a completed operation.)

Analyzing an Operations Chart. The analysis of an operations chart would duplicate that of the flow process chart. The most likely addition would be in the effort to identify possible redesign options that would eliminate individual parts or in other ways simplify the design of the object being analyzed.

Person-Machine or Multiple Activity Charts

The person-machine chart portrays the element-by-element interaction between one or more operators and one or more machines. The chart finds its primary value identifying the presence of interference between the machine-controlled operations of the machine(s) and the duties of the operator(s).

Activities Defined. When preparing the person-machine chart it is useful to distinguish among three categories of activity: independent work, combined work, and waiting. Definitions are expanded in Fig. 17.1.6.

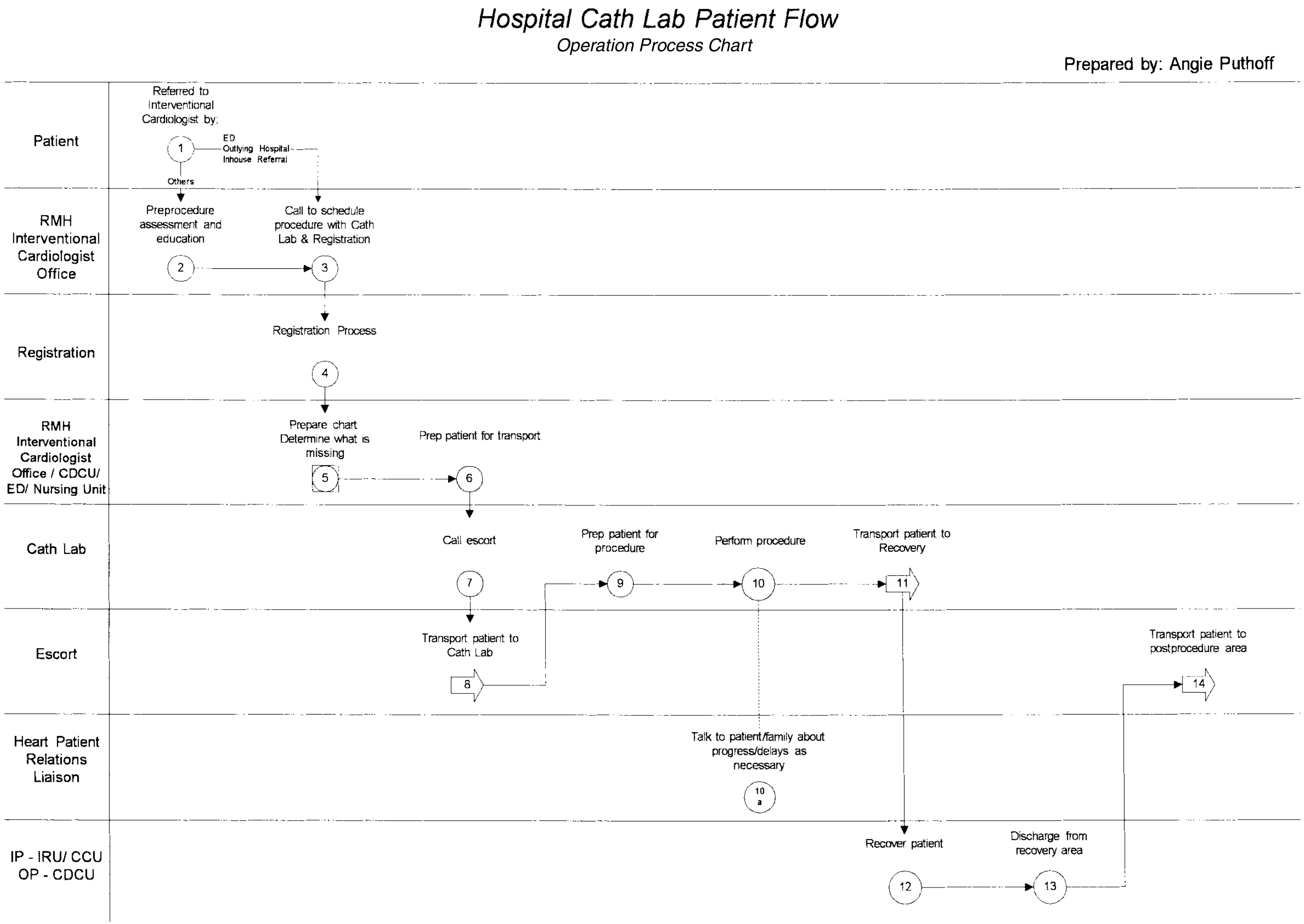

Hospital Cath Lab Patient Flow
Operation Process Chart
Prepared by: Angie Puthoff
Patient
RMH Interventional Cardiologist Office
Registration
RMH Interventional Cardiologist Office / CDCU/ ED/ Nursing Unit
Cath Lab
Escort
Heart Patient Relations Liaison
IP - IRU/ CCU
OP - CDCU
Referred to Interventional Cardiologist by:
1
ED
Outlying Hospital
Inhouse Referral
Others
Preprocedure assessment and education
2
Call to schedule procedure with Cath Lab & Registration
3
Registration Process
4
Prepare chart Determine what is missing
5
Prep patient for transport
6
Call escort
7
Transport patient to Cath Lab
8
Prep patient for procedure
9
Perform procedure
10
Talk to patient/family about progress/delays as necessary
10 a
Transport patient to Recovery
11
Recover patient
12
Discharge from recovery area
13
Transport patient to postprocedure area
14

FIGURE 17.1.5 Operation process chart.

■ *Independent Work.* For the operator, this classification means working independent of the machine or other operator, such as when getting and preparing material, inspecting finished product, and performing other work not connected with the operation of the machine. For the machine, it includes the time it is actually doing its work without the services of the operator.

□ *Combined Work.* For the operator, this classification includes working with a machine or other operator while setting up, loading, and operating a machine with hand-feed or working in cooperation with other operators. For the machine, it includes the time it is operating and requiring the services of an operator and the time it is being set up, loaded, or unloaded.

It is convenient, when analyzing a cycle of worker and machine time, to differentiate between their times when working independently (independent work) and when one depends upon the other (combined work). The blocks of time representing independent work may be shifted around independent of each other, whereas the blocks representing combined work must not be shifted with reference to each other.

▨ *Waiting.* This classification includes waiting on the part of either an operator or a machine. It occurs when one is waiting for the other. Work of an operator which prevents a machine from running, but which might be rearranged to allow the machine to operate, should be classed as independent work, and the corresponding time of the machine should be classed as waiting. This classification and graphic code place emphasis on real waiting of the machine and focus attention on work of the operator which may be rearranged to occur during machine operating time and thereby reduce machine waiting.

FIGURE 17.1.6 Person-machine chart activity codes.

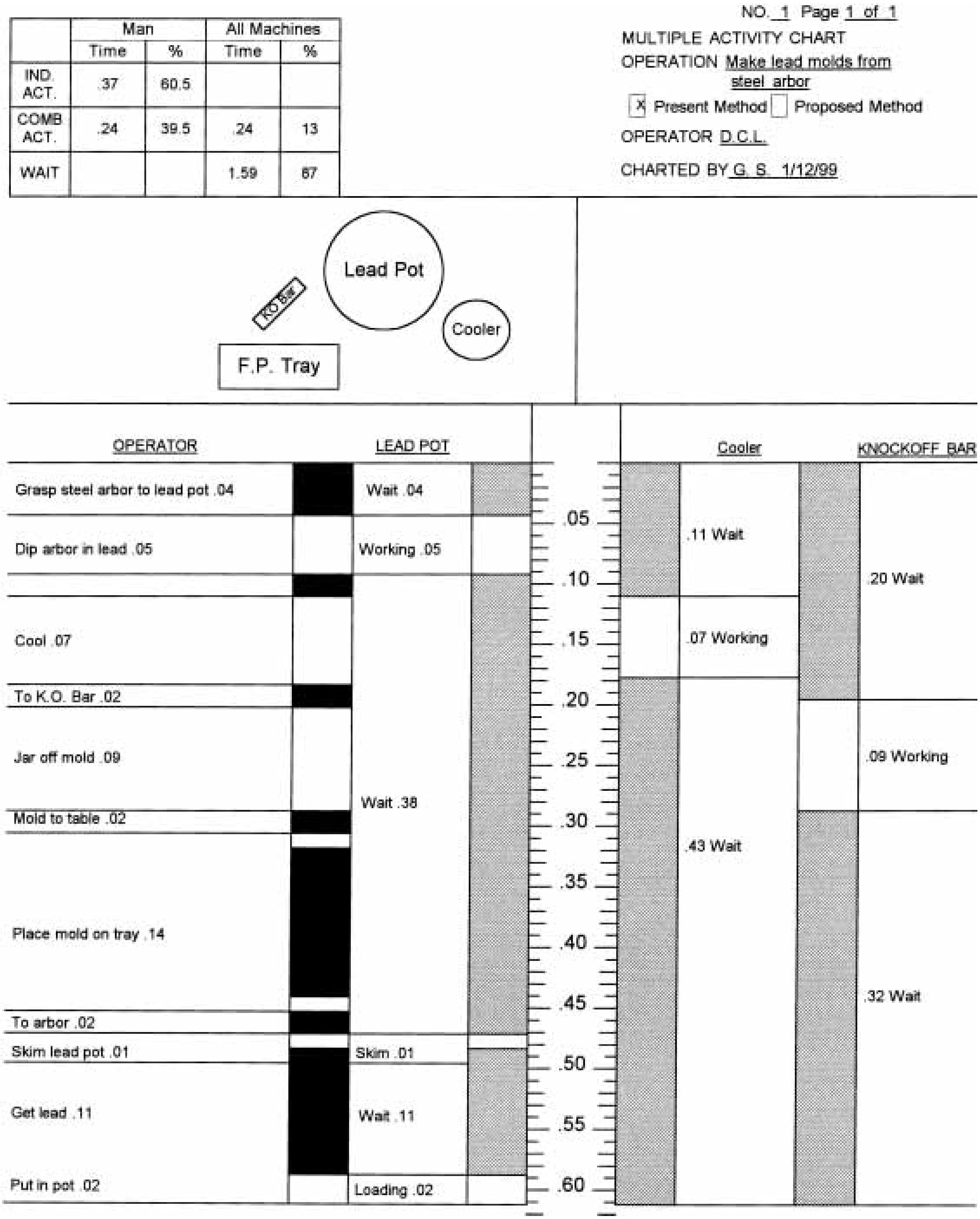
Constructing a Person-Machine Chart

1. Observe the process of interest, or conceptualize the desired process.
2. Record or synthesize the elemental activity times for each operator activity element and each machine activity element, independent of any delays caused by interference (e.g., waiting for a machine to complete a cycle before removing the finished part.)
3. Portray each operator and each machine as a vertical line on the chart (see Fig. 17.1.7).
4. Develop a time metric for the vertical scales so that at least two complete cycles can be portrayed on a chart of reasonable size.

   Note. The most useful portrayal is that of a steady-state or repetitive cycle. To attain that state, it is often helpful, when you begin constructing the chart, to assume that every machine is loaded and has completed a cycle but has not yet been attended to by an operator. This means that machine tending elements begin with "unload machine."
5. Whenever an operator services a machine, be sure that there are identical and simultaneously occurring activity elements portrayed for the operator and the machine being serviced (see Fig. 17.1.6 for definitions). Be sure that you accurately portray required interactions between the operators, as well as between machines and between operators and machines.
6. Prepare a succinct narrative explaining the portrayal and highlighting the problems revealed.

Analyzing a Person-Machine Chart

1. In searching for a high-performing solution, consider and chart alternative sequences of elements, avoiding unnecessary delays and machine interference by scheduling as much



	Man		All Machines	
	Time	%	Time	%
IND. ACT.	.37	60.5		
COMB ACT.	.24	39.5	.24	13
WAIT			1.59	87

NO. 1 Page 1 of 1
MULTIPLE ACTIVITY CHART
OPERATION Make lead molds from steel arbor
☒ Present Method ☐ Proposed Method
OPERATOR D.C.L.
CHARTED BY G. S. 1/12/99

FIGURE 17.1.7 Person-machine or multiple activity chart.

operator nonmachine time as possible (e.g., inspecting finished parts) to occur internal to the automatic or semiautomatic portions of machine cycles.

2. Keep in mind that activity elements—especially the operator-related activities are variable. It is often wise to allow 25 to 30 percent above the mean time to obtain a faithful portrayal of the situation.

Operation or Left Hand–Right Hand Charts

The operation chart is focused on a single operation that would be an element in a flow process chart. Portrayed on the chart (see Fig. 17.1.8) are the motions of the operator's two hands while performing the task being studied. This chart requires a microanalysis; typically such a fine level of detail should only be considered when cycle times are very short and the volume (number of repetitions) is very high. If the analysis calls for time-based charting of the manual and the machine-controlled elements, the chart is also referred to as a *simo* chart (for simultaneous motion).

The physical form of the operation chart varies widely, and the reader is cautioned to that realization. The immediate objective is to analyze the operation and improve it; however, in doing so, the overall goal of improving the total system performance must be kept in mind at all times.

Constructing the Operation Chart

1. Observe the operation under analysis. If possible, videotaping is the preferred observational tool since it is often difficult to capture the simultaneous motions as they occur with the unaided eye.
2. Record the basic dimensions of the workplace and the characteristics of the piece parts being handled.
3. Chart the observations on two parallel columns, one for the right hand and the other for the left.
4. Prepare a succinct narrative explaining the portrayal and highlighting the problems revealed.

Analyzing the Operator's Motions

1. Rules of thumb concerning the motion pattern of the operator are part of the core methodology that guides the analyst in seeking to optimize the work area. Table 17.1.1 is a compilation of such rules of thumb.
2. Analyze the chart for unnecessary or non-value-adding elements. (For example, using one hand as a fixture while the other is performing work is wasted effort. This can be remedied by adding a fixture to hold the work, permitting bimanual operations.)
3. Always consider ergonomic and safety issues when analyzing operator activity. Sudden, unexpected loads and repetitive motions are two important exposure variables that should be considered whenever human operations are analyzed.

COMPUTER-ASSISTED CHARTING

One of the most encouraging enhancements to the industrial engineer's analytical toolbox has been the advent of computer-assisted charting. Basically, process flowcharting software allows you to quickly and easily draw flowcharts using simple mouse- and menu-driven graphics programs.

NO. 1 Page 1 of 1

RIGHT AND LEFT HAND CHART

OPERATION Assembly of U bolt cable clamp

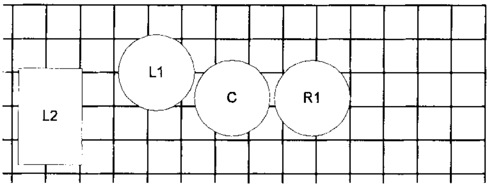
☒ Present Method ☐ Proposed Method

OPERATOR D.C.L.

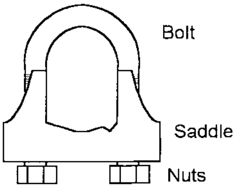
CHARTED BY G. S. 1/12/99

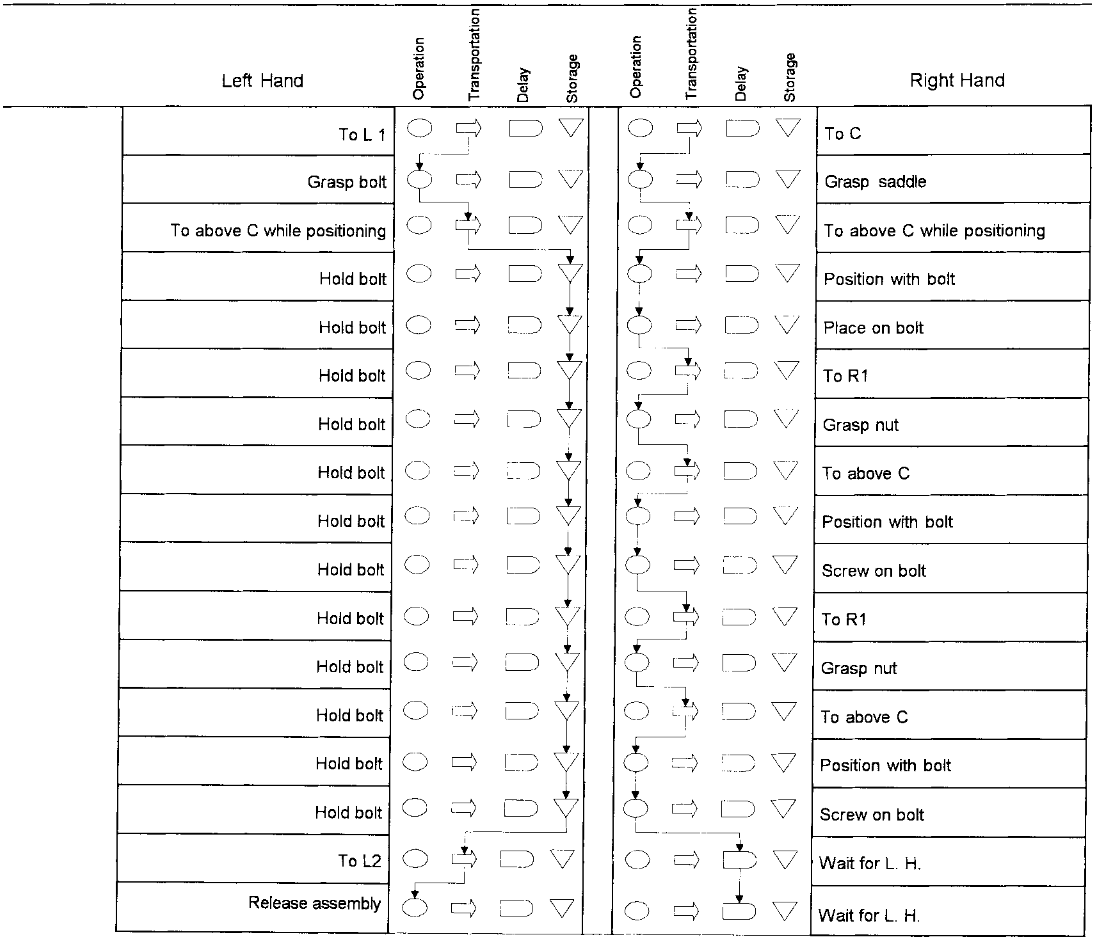
Legend
R6
R5
R4
R3
R2
R1 Nuts
C Saddles
L1 U Bolts
L2
L3
L4
L5
L6

Summary Per 1 Pieces	Present		Proposed		Difference	
	LH	RH	LH	RH	LH	RH
○ Operations	3	10				
⇨ Transportations	3	6				
D Delays	12	0				
▽ Storages	0	2				
Total	18	18				
Distance Ins.	32	46				



Parts Section


Bolt
Saddle
Nuts


Operation
Transportation
Delay
Storage
Operation
Transportation
Delay
Storage

Left Hand	Right Hand
To L 1	To C
Grasp bolt	Grasp saddle
To above C while positioning	To above C while positioning
Hold bolt	Position with bolt
Hold bolt	Place on bolt
Hold bolt	To R1
Hold bolt	Grasp nut
Hold bolt	To above C
Hold bolt	Position with bolt
Hold bolt	Screw on bolt
Hold bolt	To R1
Hold bolt	Grasp nut
Hold bolt	To above C
Hold bolt	Position with bolt
Hold bolt	Screw on bolt
To L2	Wait for L. H.
Release assembly	Wait for L. H.

FIGURE 17.1.8 Operation chart.

TABLE 17.1.1 Principles of Motion Economy

- The hands should begin and end their activity in a cycle simultaneously. If possible, they should work in opposite but symmetrical directions.
- Try to avoid idle time or using the hand as a fixture.
- Work whenever possible in an area defined by fixing the elbows at the edge of the workplace and swinging the hands in an arc (i.e., the normal work area).
- Preposition tools and parts in a definite location. Keep these objects within the normal work area if at all possible.
- Hand motions should make use of momentum from preceding activity elements whenever possible.
- Arrange the workplace to make hand motions smooth and continuous.
- If possible keep work at approximately elbow height and allow the worker to sit or stand as a matter of choice.
- If possible, use gravity to deliver parts to the operator or to carry them away from the workplace.
- Mechanize highly repetitive, short-cycle activity elements to avoid chronic ailments.

Virtually all of the software packages that support process charting are commercially produced and marketed. Examples that follow were obtained by the authors from an Internet web site search. We have selected representative illustrations of these labor-saving tools as a service to the reader. We have not compared the cost-effectiveness, ease of use, or flexibility of these packages. Furthermore, we are aware that the rate at which features of software and capabilities of the computing platforms evolve makes package-specific data of limited value. Our intent is to open the reader to the possibilities that exist.

Some charting software is available in business packages commonly available on desktop computers (e.g., Lotus Notes). In general these have some limited flowcharting capability, but they do not provide the power and capability available in specialized software.

Among the wide range of specialized charting packages available at the time this chapter was prepared are All Clear (http://www.spss.com), Process Charter (http://www.scitor.com), and Visio (http://www.visio.com). Capabilities of these packages range from simple graphics with limited features in the $50 range, to packages that provide the ability to perform dynamic process modeling in the $500 range and enterprisewide integrated packages for $1000 and up. You can easily locate a multitude of other programs by searching the Web using the key word *flowcharting.* Many of the Internet sites allow you to download demo versions of the software for hands-on evaluation. The Institute of Industrial Engineers is also a valuable resource for locating traditional and advanced industrial engineering tools.

Benefits of Computer-Assisted Charting

Automating the routine aspects of charting provides the analyst with a great deal of power and removes a substantial portion of the drudgery and non-value-adding aspects of the portrayal process. Some of the advantages include

- *Flexibility.* Most packages provide a wide range of standard shapes and free-form drawing capability. Standard shapes are available for shop floor layouts, network diagrams, flowcharts, and much more. Visio, for example, provides 2100 shapes. With the free-form drawing capability, you can create nearly any type chart you wish.
- *Ease of use.* Creating flowcharts is typically a matter of pointing to the needed icon (shapes, lines, etc.), clicking, and dragging the icon to the desired location. Adding text is usually accomplished by clicking on the deployed shapes and lines to access a text block. There are other methodologies available: for example, AllClear 4.0 allows you to generate flowcharts from text outlines, or from an outline screen provided or written in a word pro-

cessing or spreadsheet program. More advanced programs automatically reroute lines when related shapes are moved or deleted. In addition, most packages allow easy scaling of charts to accurately reflect actual workplace layouts or to achieve optimal formatting. Furthermore, these programs usually provide a means of creating customized standard templates that can greatly enhance their utility for organizationwide implementation.

- *Integration.* Many packages provide a means of coordinating and integrating the creation of various subprocess flows within a global flowchart from dispersed geographic locations. This is typically accomplished though sharing files through the Internet or networked platforms such as Windows (NT, 95) or UNIX.
- *Simulation/animation.* Packages that provide this capability permit you to ask the what-if questions and to run the alternative process configurations to identify bottlenecks.
- *Project management.* In those instances where packages provide the scheduling and Gantt charting or integrate program evaluation and review technique (PERT) and critical path method (CPM) software, the user has available the capability to manage projects as well as reengineer processes. Gantt charts portray the time sequence of activity elements and PERT and CPM portray sequential interdependencies of activity elements. In these cases the activity elements are project milestones, not process elements. Examples of PERT and Gantt charts are shown in Figs. 17.1.9 and 17.1.10.
- *Standard data.* In some cases, flowcharting packages are compatible with predetermined time systems or standard data that allow the user to synthesize processing times based on a common standard, allowing for useful comparisons of alternative configurations. This is especially useful if the organization uses a computer-based predetermined time system such as MOST to establish production standards.
- *Other features* that might be considered when choosing among the various packages include the number of different symbols or shapes (500 to 3000), interactive capability, compatibility with office software currently in use in your organization, and whether you can directly access databases or spreadsheets.

CONCLUSION

The analysis and design of human work is one of the core technologies of industrial engineering practice. The challenge presented by work design permits industrial engineers to exercise many of the facets of their academic preparation, including problem solving, human factors/ human performance, and scheduling and sequencing of operations, to name but a few. Most of the techniques included in this monograph are drawn from the traditional tools of the industrial engineer. What makes the change agent of today so different from the efficiency expert of the past is that the systems view of the work environment requires a much more expansive perspective of what falls within the boundaries of the problem at hand. Another difference is the realization that much of the real wisdom and expertise about the nature of work resides with the individual who performs the work on a daily basis. Empowering the worker enhances the role of the industrial engineer.

We want to caution the reader that these techniques all treat time values as fixed and deterministic rather than variable. In those instances in which sequential variable activity elements are tightly coupled, it is unreasonable to expect that a summation of the mean times will represent the actual performance.

When making use of the representational aids presented in this chapter, we urge the reader to maintain the proper perspective regarding all technology: the tools are intended to serve you and enhance your effectiveness as an analyst. Don't become a slave to them. You can allow yourself some latitude to realize this objective; however, where symbols or formats have been standardized, innovation can be counterproductive.

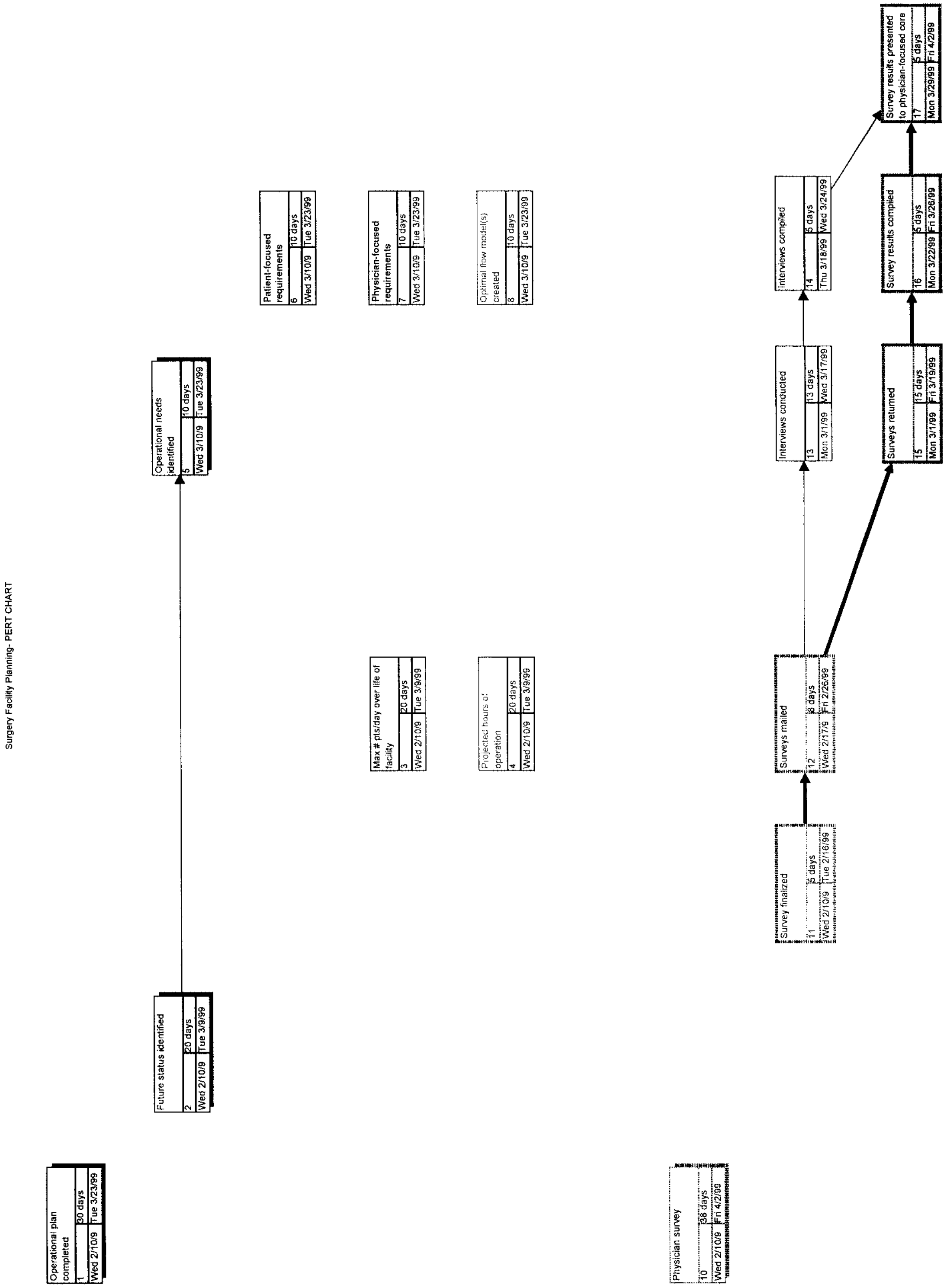

Surgery Facility Planning- PERT CHART
Operational plan completed
1
30 days
Wed 2/10/9
Tue 3/23/99
Future status identified
2
20 days
Wed 2/10/9
Tue 3/9/99
Max # pts/day over life of facility
3
20 days
Wed 2/10/9
Tue 3/9/99
Projected hours of operation
4
20 days
Wed 2/10/9
Tue 3/9/99
Operational needs identified
5
10 days
Wed 3/10/9
Tue 3/23/99
Patient-focused requirements
6
10 days
Wed 3/10/9
Tue 3/23/99
Physician-focused requirements
7
10 days
Wed 3/10/9
Tue 3/23/99
Optimal flow model(s) created
8
10 days
Wed 3/10/9
Tue 3/23/99
Physician survey
10
38 days
Wed 2/10/9
Fri 4/2/99
Survey finalized
11
5 days
Wed 2/10/9
Tue 2/16/99
Surveys mailed
12
8 days
Wed 2/17/9
Fri 2/26/99
Interviews conducted
13
13 days
Mon 3/1/99
Wed 3/17/99
Interviews compiled
14
5 days
Thu 3/18/99
Wed 3/24/99
Surveys returned
15
15 days
Mon 3/1/99
Fri 3/19/99
Survey results compiled
16
5 days
Mon 3/22/99
Fri 3/26/99
Survey results presented to physician-focused core
17
5 days
Mon 3/29/99
Fri 4/2/99

FIGURE 17.1.9 Example of PERT chart.

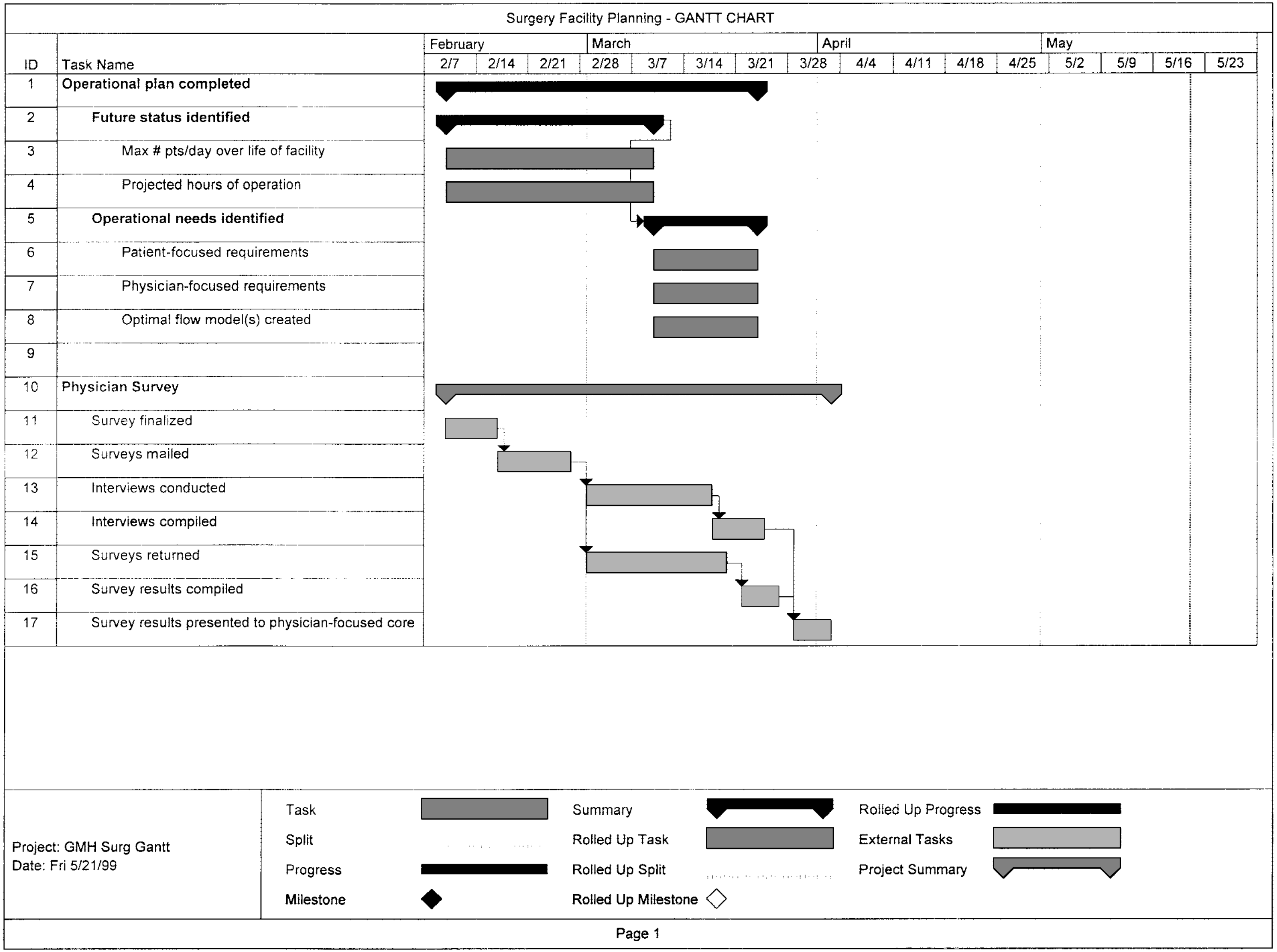


FIGURE 17.1.10 Example of Gantt chart.

BIOGRAPHIES

George L. Smith, Ph.D., P.E., is engaged as a private consultant working with corporate executives, their management teams and in-house staff supporting their initiatives in organizational transformation. Areas of support include performance improvement planning and implementation, creating and using balanced scorecards, change management, and large-scale change. He served as a faculty member in industrial and systems engineering (ISE) at the Ohio State University for 27 years (1968 to 1995) and has continued to teach as an emeritus professor. He was chair of the ISE Department for 12 years and associate dean of academic affairs for the College of Engineering for two. Smith has been named a Fellow of the Institute of Industrial Engineers, the Human Factors and Ergonomics Society, and the World Academy of Productivity Science. He was president of the Society for Engineering and Management Systems from 1997 to 1999. Smith is the author of a book on work measurement and many technical articles.

Dan Loch is vice president, General Services and director of Management Engineering for Grant/Riverside Methodist Hospitals (G/RMH). His major efforts are directed toward empowering units to exceed the expectations of internal and external customers through project management, performance measurement, and visible management systems. Management Engineering is a self-directed unit supporting process reengineering in all areas of G/RMH. An industrial engineering graduate of Youngstown State University, he is past president of the Columbus, Ohio, chapter of the Institute of Industrial Engineers.

CHAPTER 17.2
STOPWATCH TIME STUDY

Clifford N. Sellie
Standards International, Inc.
Northbrook, Illinois

Time study is used to determine time standards (targets) for planning, costing, scheduling, hiring, productivity evaluation, pay plans, and the like. Time standards may be determined by a number of different time study techniques: (1) They can be based on historical records of time taken in the past to perform the task. These calculations of historical times can be based on straight arithmetic averages or sophisticated statistical analyses. (2) Another technique (sometimes called reasonable expectancies) is use of estimates by an individual knowledgeable of the time that it would take a qualified operator working at an acceptable performance level to do the job. (3) A third technique is predetermined times. Here the tasks are analyzed as to the work content and then predetermined times for the work segments are summed up to get the total time for the task. (4) The fourth and most often used technique is stopwatch time study.

Stopwatch time study is the most popular method of work measurement. It was first developed by Frederick W. Taylor before the turn of the twentieth century. It is now used worldwide to determine the time required to do work.

This chapter will discuss the basic principles and practices for setting fair, consistent stopwatch standards.

TIME STUDY

Time study may be defined as follows: Time study is a procedure used to measure the time required by a qualified operator working at the normal performance level to perform a given task in accordance with a specified method [1]. In practice, time study usually includes methods study. The industrial engineer (time study analyst) has to observe the methods while making a time study. The definition of time study states that the task measured is performed with a specified method. It is desirable, while the time study is being conducted, for the analyst to also look for opportunities for methods improvement. Many companies use the term *methods/standards analyst* to encourage the time study person to look for methods improvements while observing the methods for time study purposes. This chapter reviews the principles and techniques in using stopwatch time studies to establish allowed times. Section 3 of this handbook reviews principles and techniques of methods analyses.

Figure 17.2.1 presents a graphic analysis of the steps involved in establishing a stopwatch time standard. The first step is methods study and the second step time study. Methods study is shown first to emphasize the fact that the method should always be studied, improved, and standardized before the time study is begun. Time study begins with the category "selection of operator."

STOPWATCH TIME STUDY TOOLS

The stopwatch equipment used to make a time study varies widely. It has often been said, and sometimes proved, that a good time study technician can make a usable time study with only the back of an envelope, a wristwatch, and a stubby pencil. This is a boast that has been responsible for many poor quality standards and the failure of many time study analysts.

It is desirable that the time study be accurate, understandable, and verifiable. The time study tools used can help or hinder the analyst in meeting these requirements. A few of the essential tools that are needed by the time study analyst to make a good time study include

1. Time study watch—digital display (electronic) or sweep hand (mechanical).
2. Clipboard with bracket—to hold the time study forms.
3. Time study form(s)—(repetitive and nonrepetitive) that provide for the written details to be covered in the time study.
4. Pencil.
5. Tape, ruler, or micrometer—depending on the distances involved and the precision with which they need to be measured.
6. Stroboscope—for measuring machine and equipment settings. Strobe lights (electronic stroboscopes) are the most accurate and usually the easiest to use.
7. Calculator or a programmed personal computer (PC)—to do the arithmetic calculations involved in time study.

Stopwatches: Basic Types

The watch used when making a time study is the most important of these tools. The type of watch used should vary with the purposes of the time study. An ordinary wristwatch may be adequate for overall times and/or lengthy cycles. For most time studies, stopwatches are required. Sweep hand (mechanical) watches provide reasonable accuracy and readability (for cycles 0.03 minute and over). Most digital watches use quartz crystals that provide accuracy of plus and minus 0.00005. The digital display of numbers (electronic stopwatches) is much easier to read, since the numbers displayed can be frozen while the time study analyst reads and writes down the time. Also, the recorded time values tend to be more accurate when based on display of numbers.

The most common stopwatch (mechanical or electronic) is a decimal minute watch. Decimal hour watches and decimal second watches are also available. Decimal seconds are common in sports timing. The decimal hour watch is often used in conjunction with methods time measurement (MTM) studies, since MTM time values (time measurement units [TMUs]) are in decimal hours.

However, decimal minutes are usually preferred for industrial time studies. It is easy for most of us to visualize a time interval in decimal minutes: a tenth of a minute, a half of a minute, or a minute (as contrasted with thousandths of an hour or 1.2 seconds).

Stopwatches are available in two modes:

- Snapback mode—the watch shows the time for each element, and automatically resets to zero for the start of each element.
- Cumulative mode (continuous mode)—the watch shows the total elapsed time from the start of the first element.

Some digital watches (offered by Meylan, New York, and FAEHR Electronic Timers, Rockford, Illinois) are built into a clipboard that provides two displays: the time for each event (snapback mode) and the total time (cumulative mode) (see Fig. 17.2.2).

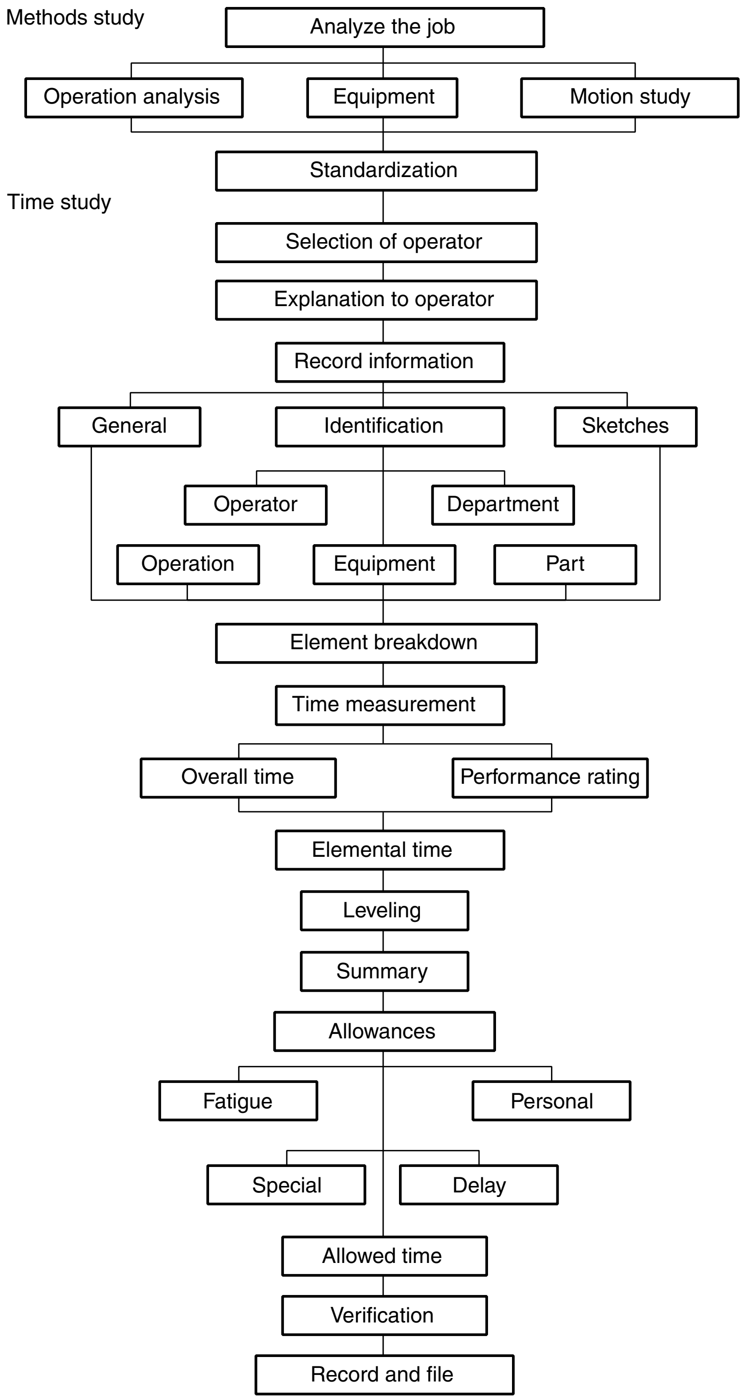

Methods study
Analyze the job
Operation analysis
Equipment
Motion study
Standardization
Time study
Selection of operator
Explanation to operator
Record information
General
Identification
Sketches
Operator
Department
Operation
Equipment
Part
Element breakdown
Time measurement
Overall time
Performance rating
Elemental time
Leveling
Summary
Allowances
Fatigue
Personal
Special
Delay
Allowed time
Verification
Record and file

FIGURE 17.2.1 Graphic analysis of the steps involved in establishing a time standard [2].

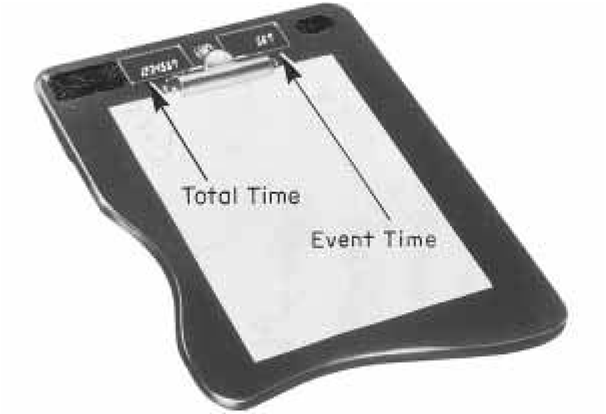

Total Time
Event Time

FIGURE 17.2.2 Dual display digital boardwatch. (*Courtesy of FAEHR Electronic Timers, Rockford, Illinois.*)

The most popular stopwatches continue to be single display, whether sweep hand or digital (see Figs. 17.2.3 and 17.2.4).

Comparison of Sweep Hand and Digital Watches. There are advantages to the sweep hand or mechanical stopwatch and the digital or electronic watch. The sweep hand, the most commonly used, is manufactured in large quantities, which cuts manufacturing costs and sales prices. Electronic watches are produced in large volume in sports timing models, but in small quantities in good industrial timing models. Accordingly, the price of a quality sweep hand stopwatch for industrial use is about one-half the price of a comparable quality electronic watch.

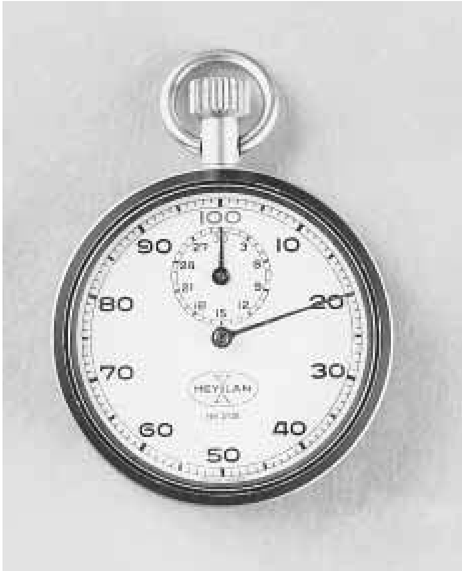

100
10
20
30
40
50
60
70
80
90
MEYLAN

FIGURE 17.2.3 Sweep hand watch. (*Courtesy of Meylan Corporation, New York, New York.*)

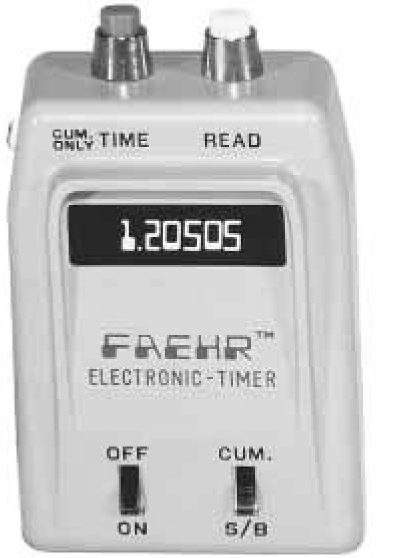

CUM. ONLY TIME
READ
1.20505
FAEHR™
ELECTRONIC-TIMER
OFF
ON
CUM.
S/B

FIGURE 17.2.4 Single display digital watch. (*Courtesy of FAEHR Electronic Timers, Rockford, Illinois.*)

Mechanical stopwatches also have a psychological advantage. More people are acquainted with the sweep hand type of stopwatch and most of us are more comfortable with tools with which we are familiar.

This psychological advantage is gradually diminishing as the result of increasing exposure to electronic stopwatches. There are some technical advantages to the digital display of electronic stopwatches. Digital stopwatches provide frozen display of exact time in actual numbers. That is much easier to read than trying to read the exact time on a sweep hand. Digital displays tend to avoid reading errors and to reduce disputes about the readings.

The action of an electronic timer is practically instantaneous. The time required to snap a mechanical watch back to zero, while not large, is considerably greater than that required by the electronic timer. There is an inherent error in using mechanical watches for snapback time studies due to the time needed to snap the watch back to zero. Laboratory studies made with the aid of slow motion pictures show that an error of 3 to over 9 percent will occur on each element of 0.006 minute duration when using a mechanical stopwatch [3].

The objection to lost time in snapback studies is minimal when using electronic timers. The lost time is less than 0.0003 minute per snapback when using an electronic stopwatch [4].

Time Study Clipboard

The observer generally stands and moves about when making a stopwatch time study. The observer must simultaneously: (1) watch the movements of the operator, (2) keep the stopwatch within the line of vision so the time can be observed at the end of each element, and (3) record the individual time readings on the time study form. A variety of time study clipboards are available from different suppliers. Dual display digital timers build the timer into the clipboard (see Fig. 17.2.2). Figure 17.2.5 shows a separate time study board (clipboard) available with a clamp. This "body form" shape is a little more comfortable for use than the customary straight rectangle shape.

The "RateSetter" System

One of the latest developments in this field is the "RateSetter" system. It is shown in Fig. 17.2.6. The timer is so designed that once the time study observations have been entered into the timer, the data can be transmitted electronically to an IBM-compatible PC and the PC can then perform all of the calculations required to complete the time study. A major advantage of the "RateSetter" system is automatic adherence to correct time study procedures. (This saves training time and focuses on methods analysis instead of time study rules.) The time saved for methods analysis is very important and results in better methods, increased output, and lower costs.

The operation to be studied is divided into elements in the normal fashion. The element description is handwritten on the form. The element number is entered into the timer with the keyboard. The study is started by pressing the Read button on the right side of the board. The Read button is then pressed at the end of each element. When the last element is entered, the Cycle liquid crystal display (LCD) window automatically changes to cycle 2 and the study is continued for as many cycles as needed. The performance rating, or leveling factor, can be applied to each element by using the keyboard.

The Time counter LCD window is like a continuous reading stopwatch. The readings can be recorded manually on the form to record foreign elements, elements performed out of order, or any other abnormal occurrence in the normal cycle.

The time readings can be in hours to five decimal places (same as MTM-TMU times), in decimal minutes to three decimal places, or in hours, minutes, and seconds to two decimal places.

The windows on the top of the board are LCD displays that can be contrast adjusted for any lighting conditions. Memory and Battery Status alert the analyst to take the necessary action to either dump the memory or recharge the battery.

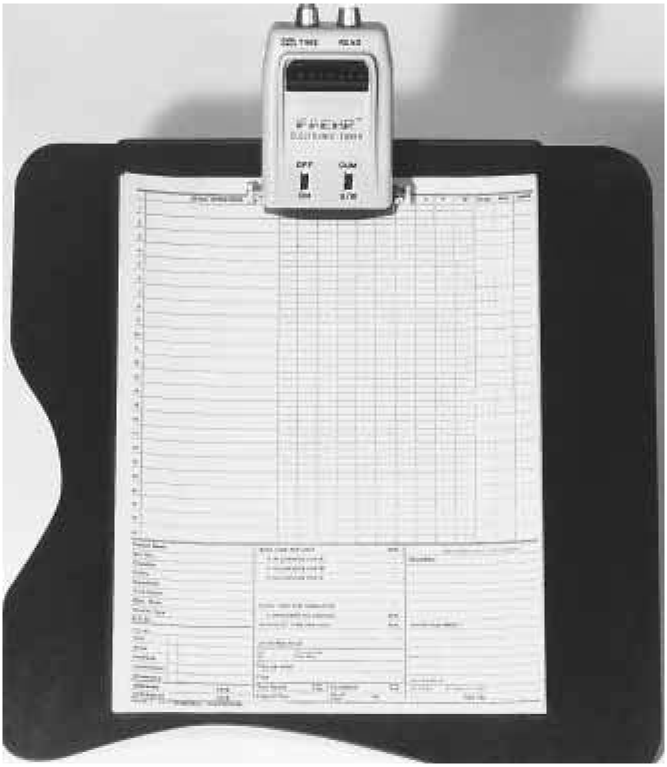


FIGURE 17.2.5 Separate time study board (clipboard) with clamp. (*Courtesy of FAEHR Electronic Timers, Rockford, Illinois.*)

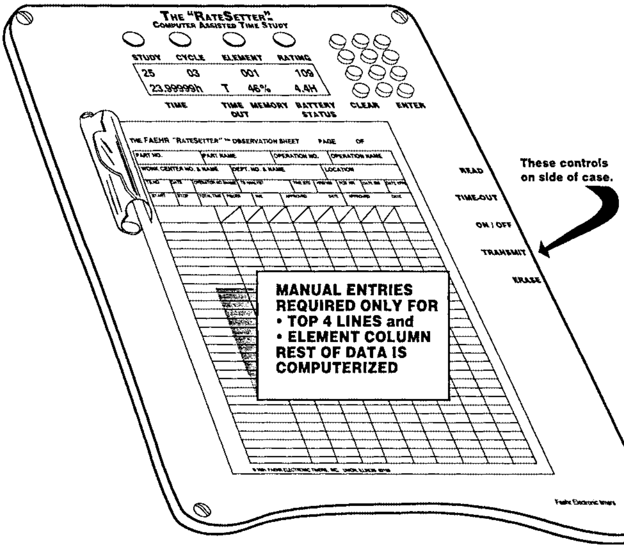

The "RateSetter"™
Computer Assisted Time Study
STUDY
CYCLE
ELEMENT
RATING
25
03
001
109
23.99999h
T
46%
4.4H
TIME
TIME OUT
MEMORY
BATTERY STATUS
CLEAR
ENTER
THE FAEHR "RATESETTER"™ OBSERVATION SHEET
PAGE
OF
READ
TIME-OUT
ON / OFF
TRANSMIT
ERASE
These controls on side of case.
MANUAL ENTRIES REQUIRED ONLY FOR
• TOP 4 LINES and
• ELEMENT COLUMN
REST OF DATA IS COMPUTERIZED

FIGURE 17.2.6 The FAEHR electronic timer. (*Courtesy of FAEHR Electronic Timers, Rockford, Illinois.*)

At the end of the study the analyst turns off the timer. This clears the top four LCD displays, and the timer is ready for another study.

The timer can be connected to an IBM-compatible PC that has the "RateSetter" software system installed. The elemental data can then be sent from the timer memory to the PC. The PC can then

- Determine the individual element times plus mean and median element averages.
- Adjust for the performance rating.
- Summarize the results to determine the time standard per piece, and the pieces per hour.

The software can be adjusted to fit individual company needs.

Time Study Forms

The time study forms that are used in Figs. 17.2.7 and 17.2.8 are typical. Many different forms are available from suppliers. Select or design one to fit your needs. The form should provide space for certain descriptive information that must be recorded at the time the study is made if the study is to be of value in the future. This information falls into two categories:

1. One category provides preliminary basics, such as the product, name of operator studied, process routing, machines used, tools used, workplace layout, date, and observer's name.
2. The second category describes the study, identifies the elements studied, lists the stopwatch readings, gives the performance rating and the standards calculations, and the like. Ideally, the element descriptions on the time study form provide a narrative description of everything the worker does to correctly accomplish the job.

The description of the method used on the job should include available methods improvements that can be installed for the current job. This should include all methods improvements—previously discovered methods ideas, reported and unreported—plus current ideas discovered by the methods standards analyst and ideas recommended by the operator, the supervisor, and others.

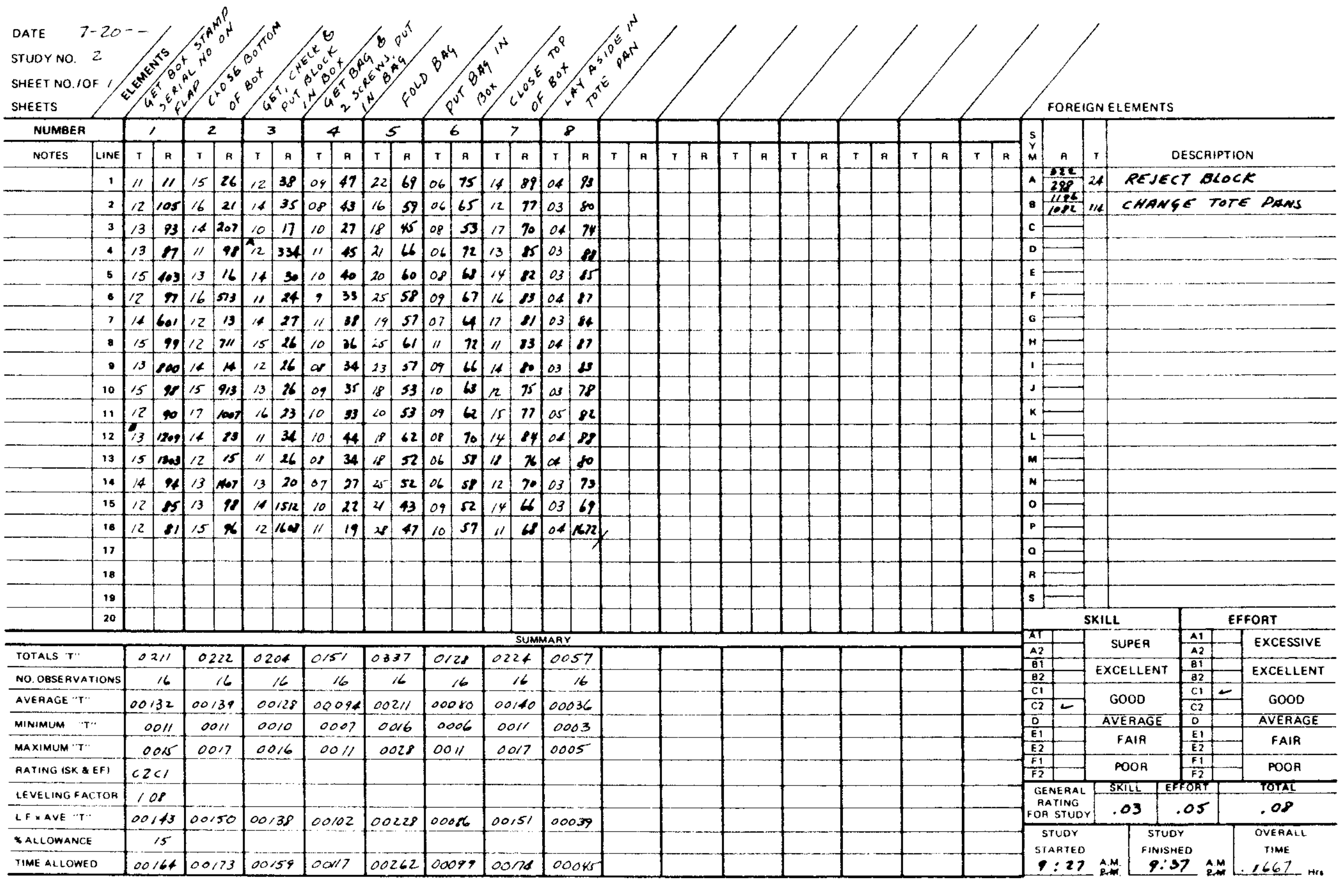
It is desirable to have a methods suggestion file or computer listing, where approved but not implemented methods improvements are noted. Approved but not implemented ideas are often forgotten unless there is a convenient, reliable reminder the next time a job is done. In a competitive world, neither poor methods nor poor standards can be afforded.

Examples of Filled-in Forms. Figures 17.2.7 and 17.2.8 show a time study that was made using a decimal hour watch. The continuous method of recording watch readings was followed. As a result, the study tells the complete story of the sequence in which all elements of the operation were performed. Every moment of time consumed during the period in which the study was made is accounted for. When the normal sequence of operations was interrupted, both the time consumed and a description of the nature of the interruption were recorded.

The completed study reads like the page of a book. It starts at the top left, reads across to the right, down one line, and so on. Foreign elements or interruptions appear as marginal notes [7].

The usual number of readings on a repetitive time study form are a minimum of 8, up to and including 12. Ten observations are the most common, probably because the arithmetic is simpler using 10 observations. Figures 17.2.7 and 17.2.8 show copies, front and back, of a repetitive time study form.

Occasionally, it is desirable to take only a few complete readings. This is most often done on low-volume or nonrepetitive work. Figure 17.2.9 is a copy of one side of a nonrepetitive time study form. This form provides space for listing a large number of elements per operation. The back of the form is usually the same whether for repetitive or nonrepetitive time study.



DATE 7-20--
STUDY NO. 2
SHEET NO./OF 1
SHEETS

ELEMENTS		GET BOX STAMP SERIAL NO ON FLAP		CLOSE BOTTOM OF BOX		GET, CHECK & PUT BLOCK IN BOX		GET BAG & 2 SCREWS, PUT IN BAG		FOLD BAG		PUT BAG IN BOX		CLOSE TOP OF BOX		LAY ASIDE IN TOTE PAN	
NUMBER		1		2		3		4		5		6		7		8	
NOTES	LINE	T	R	T	R	T	R	T	R	T	R	T	R	T	R	T	R
	1	11	11	15	26	12	38	09	47	22	69	06	75	14	89	04	93
	2	12	105	16	21	14	35	08	43	16	59	06	65	12	77	03	80
	3	13	93	14	207	10	17	10	27	18	45	08	53	17	70	04	74
	4	13	87	11	98	A 12	334	11	45	21	66	06	72	13	85	03	88
	5	15	403	13	16	14	30	10	40	20	60	08	68	14	82	03	85
	6	12	97	16	513	11	24	9	33	25	58	09	67	16	83	04	87
	7	14	601	12	13	14	27	11	38	19	57	07	64	17	81	03	84
	8	15	99	12	711	15	26	10	36	25	61	11	72	11	83	04	87
	9	13	800	14	14	12	26	08	34	23	57	09	66	14	80	03	83
	10	15	98	15	913	13	26	09	35	18	53	10	63	12	75	03	78
	11	12	90	17	1007	16	23	10	33	20	53	09	62	15	77	05	82
	12	B 13	1209	14	23	11	34	10	44	18	62	08	70	14	84	04	88
	13	15	1303	12	15	11	26	08	34	18	52	06	58	18	76	04	80
	14	14	94	13	1407	13	20	07	27	25	52	06	58	12	70	03	73
	15	12	85	13	98	14	1512	10	22	21	43	09	52	14	66	03	69
	16	12	81	15	96	12	1608	11	19	28	47	10	57	11	68	04	1672
	17																
	18																
	19																
	20																

SUMMARY

TOTALS "T"	0211	0222	0204	0151	0337	0128	0224	0057
NO. OBSERVATIONS	16	16	16	16	16	16	16	16
AVERAGE "T"	00132	00139	00128	00094	00211	00080	00140	00036
MINIMUM "T"	0011	0011	0010	0007	0016	0006	0011	0003
MAXIMUM "T"	0015	0017	0016	0011	0028	0011	0017	0005
RATING (SK & EF)	C2C1							
LEVELING FACTOR	1 08							
L F × AVE "T"	00143	00150	00138	00102	00228	00086	00151	00039
% ALLOWANCE	15							
TIME ALLOWED	00164	00173	00159	00117	00262	00099	00174	00045

FOREIGN ELEMENTS

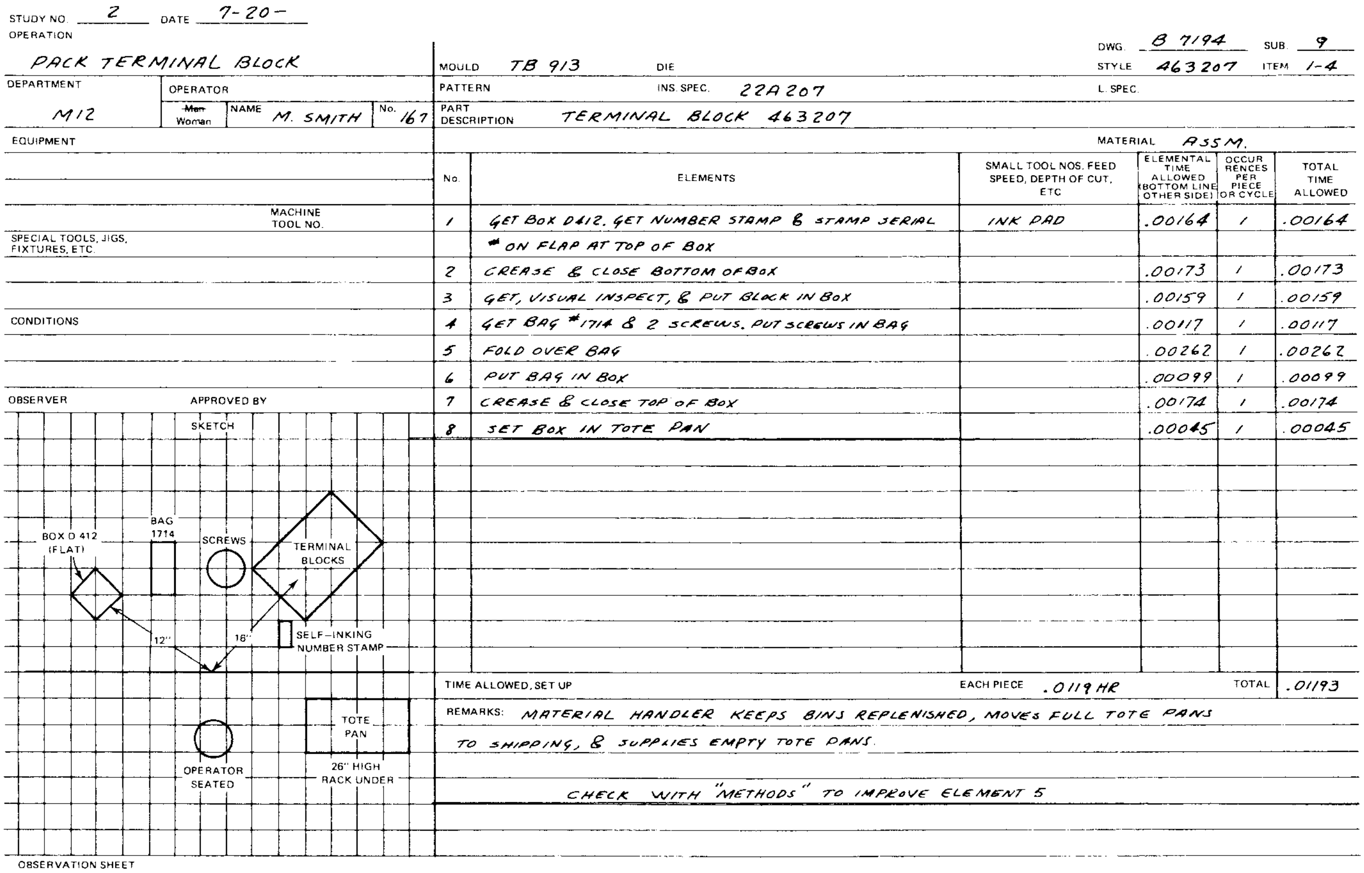
SYM	R	T	DESCRIPTION
A	322 298	24	REJECT BLOCK
B	1196 1072	114	CHANGE TOTE PANS
C			
D			
E			
F			
G			
H			
I			
J			
K			
L			
M			
N			
O			
P			
Q			
R			
S			

SKILL			EFFORT		
A1		SUPER	A1		EXCESSIVE
A2			A2		
B1		EXCELLENT	B1		EXCELLENT
B2			B2		
C1		GOOD	C1	✓	GOOD
C2	✓		C2		
D		AVERAGE	D		AVERAGE
E1		FAIR	E1		FAIR
E2			E2		
F1		POOR	F1		POOR
F2			F2		

GENERAL RATING FOR STUDY	SKILL	EFFORT	TOTAL
	.03	.05	.08

STUDY STARTED 9:27 [✓ A.M.] P.M.
STUDY FINISHED 9:37 [✓ A.M.] P.M.
OVERALL TIME .1667 Hrs

FIGURE 17.2.7 Time study form—front [5].



STUDY NO. 2 DATE 7-20-

OPERATION PACK TERMINAL BLOCK

MOULD TB 913 DIE

DWG. B 7194 SUB. 9

STYLE 463207 ITEM 1-4

DEPARTMENT M12

OPERATOR ~~Man~~ Woman NAME M. SMITH No. 167

PATTERN INS. SPEC. 22A 207 L. SPEC.

PART DESCRIPTION TERMINAL BLOCK 463207

EQUIPMENT

MATERIAL ASSM.

MACHINE TOOL NO.

SPECIAL TOOLS, JIGS, FIXTURES, ETC.

CONDITIONS

OBSERVER APPROVED BY

No.	ELEMENTS	SMALL TOOL NOS. FEED SPEED, DEPTH OF CUT, ETC	ELEMENTAL TIME ALLOWED (BOTTOM LINE OTHER SIDE)	OCCURRENCES PER PIECE OR CYCLE	TOTAL TIME ALLOWED
1	GET BOX D412, GET NUMBER STAMP & STAMP SERIAL # ON FLAP AT TOP OF BOX	INK PAD	.00164	1	.00164
2	CREASE & CLOSE BOTTOM OF BOX		.00173	1	.00173
3	GET, VISUAL INSPECT, & PUT BLOCK IN BOX		.00159	1	.00159
4	GET BAG #1714 & 2 SCREWS. PUT SCREWS IN BAG		.00117	1	.00117
5	FOLD OVER BAG		.00262	1	.00262
6	PUT BAG IN BOX		.00099	1	.00099
7	CREASE & CLOSE TOP OF BOX		.00174	1	.00174
8	SET BOX IN TOTE PAN		.00045	1	.00045

TIME ALLOWED, SET UP EACH PIECE .0119 HR TOTAL .01193

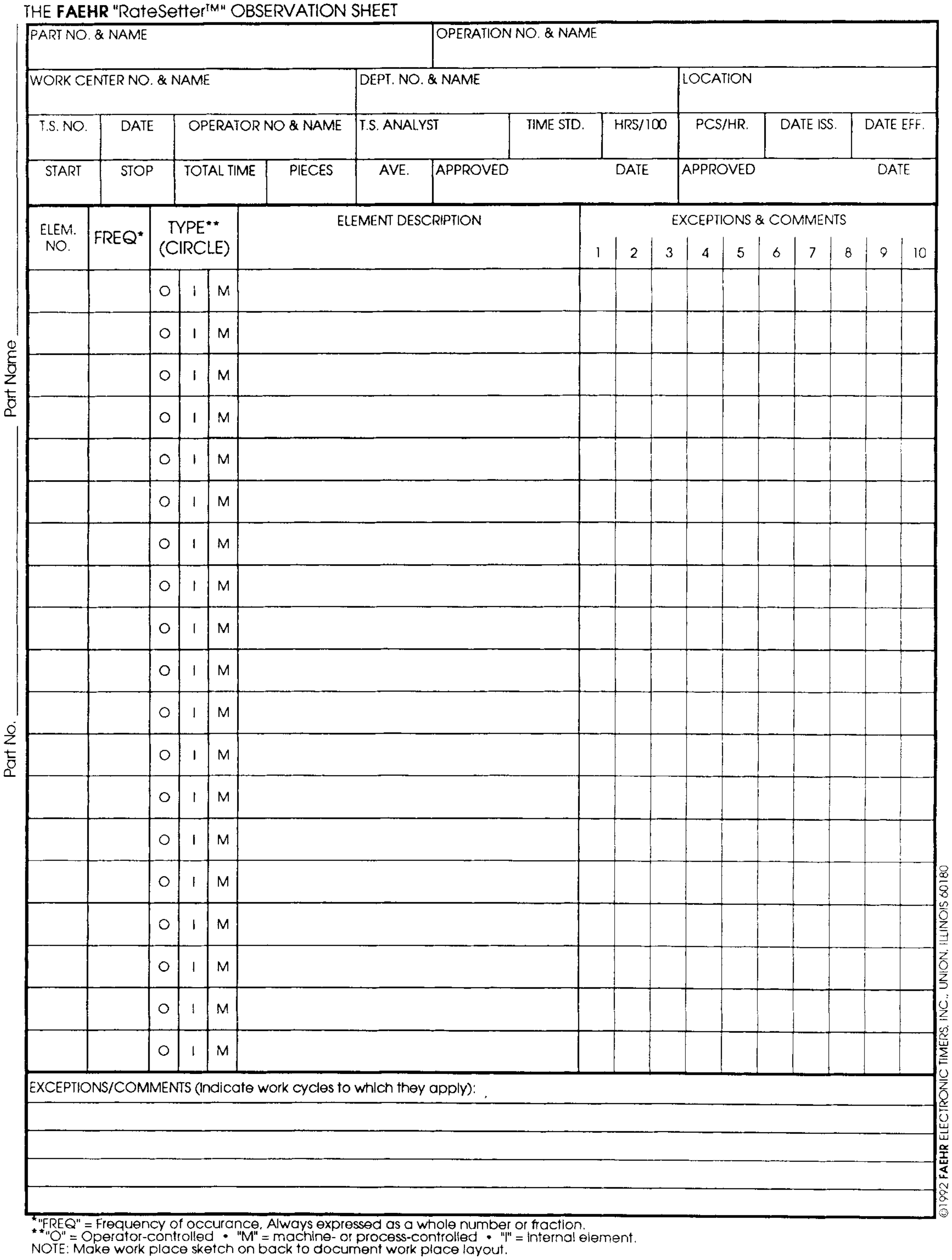
REMARKS: MATERIAL HANDLER KEEPS BINS REPLENISHED, MOVES FULL TOTE PANS TO SHIPPING, & SUPPLIES EMPTY TOTE PANS.

CHECK WITH "METHODS" TO IMPROVE ELEMENT 5

SKETCH

OBSERVATION SHEET

FIGURE 17.2.8 Time study form—back [6].



THE **FAEHR** "RateSetter™" OBSERVATION SHEET

Part Name

Part No.

PART NO. & NAME				OPERATION NO. & NAME				
WORK CENTER NO. & NAME			DEPT. NO. & NAME			LOCATION		
T.S. NO.	DATE	OPERATOR NO & NAME	T.S. ANALYST	TIME STD.	HRS/100	PCS/HR.	DATE ISS.	DATE EFF.
START	STOP	TOTAL TIME	PIECES	AVE.	APPROVED	DATE	APPROVED	DATE

ELEM. NO.	FREQ*	TYPE** (CIRCLE)			ELEMENT DESCRIPTION	EXCEPTIONS & COMMENTS									
						1	2	3	4	5	6	7	8	9	10
		O	I	M											
		O	I	M											
		O	I	M											
		O	I	M											
		O	I	M											
		O	I	M											
		O	I	M											
		O	I	M											
		O	I	M											
		O	I	M											
		O	I	M											
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		O	I	M											
		O	I	M											
		O	I	M											
		O	I	M											
		O	I	M											
		O	I	M											

EXCEPTIONS/COMMENTS (Indicate work cycles to which they apply):

*"FREQ" = Frequency of occurance. Always expressed as a whole number or fraction.
**"O" = Operator-controlled • "M" = machine- or process-controlled • "I" = Internal element.
NOTE: Make work place sketch on back to document work place layout.

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FIGURE 17.2.9 The FAEHR “RateSetter™” observation sheet [8].

Any time study form that meets the requirement of permitting the analyst to be explicit in telling the complete story is satisfactory. The word *explicit* is emphasized. It should be possible for anyone familiar with the operations to reconstruct from the time study description the methods used when the stopwatch study was made. This methods information can be useful to the operator, setup person, and line supervisor in setting up the job the next time so the methods used by the operator will be the same as the methods on which the standard is set. This methods information is essential in proving the standard right (or wrong) if the standard is questioned—especially if the standard goes to arbitration. It is also essential when methods and standards changes are to be made.

A good test of a time study write-up is to use it to reconstruct a job in accordance with the methods specified on the time standard. Provision is made on the front and back of the time study form to record identifying and other pertinent information. These data should be recorded at the time the study is made. Records should be made to show complete identification of the operator; the part upon which the operation is being performed; the machines, tools, and equipment being used; the operation; and the department in which the operation is performed. Sketches, for which space is provided, are generally a desirable and necessary adjunct to verbal descriptions. These sketches preferably should show the workplace layout, or they can illustrate the part upon which the operation is performed. Some companies attach a photograph of the workplace or of the part to the time study form to illustrate the conditions at the time the study was made.

The recording of complete information is of the utmost importance and cannot be too highly stressed. Figure 17.2.8 shows typical information recorded on the time study form. Note that under Remarks, the method of bringing material to the workplace and removing it from the workplace has been described. Such data, unless recorded at the time the study is made, become lost in limbo when later trying to reconstruct the conditions to which the standard applies.

Most of the heading of the spaces used to record information are self-explanatory. The Ins. Spec. heading is used to record the number of the inspection specification, if such data are available in the plant. The L. Spec. heading identifies the electrical specifications number where it is pertinent.

TIME STUDY PROCEDURE

When the method has been established, conditions standardized, and the operators trained to follow the approved method, the job is ready for a stopwatch study.

Selection of the Operator

The operator studied is important. Time studying the wrong operator can (1) double the difficulty of making the study and (2) decrease the accuracy of the standard. The operator should be one who works with good skill and effort using the approved method. The time study analyst, by applying the performance rating procedure correctly, can arrive at the same final time standard within practical limits, regardless of whether the operator works quickly or slowly. From every viewpoint, however, it is better if the stopwatch standard is based on observation of an effective, cooperative worker performing at an acceptable performance level. As a rule of thumb, it is undesirable to try to rate an operator working a greater variance than 25 percent above or below 100 percent.

Show the Work Methods and Time Study Readings

Time study should not be considered a secret document confined to the use of the analyst. It should be an accurate recording of informative data that cover the best and most efficient manner of doing the work under the conditions expected to be in effect when the job is run.

It should be a set of instructions that can be used (1) by supervisors and setup personnel in arranging for the job to be run, and (2) also by the workers in performing their jobs. Time studies should be correct and subject to proof of correctness.

The operator, the supervisor, and the steward (in a union shop) should be shown the completed results. All details should be freely discussed with them; check studies should be conducted of any elements that may be questioned, and an effort made to fully answer any questions concerning the study. An air of mystery or of hiding facts leads to distrust and "we-against-them" attitudes that prejudice both the study and the working conditions.

Explanation to the Operator and the Line Supervisor

The manner in which the operator is approached at the beginning of the study is important. The analyst should be courteous and honest, and show a recognition of and a respect for the operator's problems. The analyst must be frank in dealing with the operator on questions about the operations being studied and on the time studies. The analyst must be able to explain in clear, nontechnical words all steps in the actual stopwatch procedure.

When the analyst is not familiar with the operation, the analyst must not try to hide that unfamiliarity but should ask questions of the operator or supervisor or of anyone else in position to explain the operation. The analyst should be open and above reproach. Efforts to hide stopwatch studies can be self-defeating. They create distrust of the analyst. They cause "game playing" by the operator to trick the analyst in turn.

The analyst should stand alongside the worker, unless the latter's duties require moving sideways in the performance of the work. The analyst should not stand directly behind the operator while making the study. This practice causes the operator to become restless and suspicious as to what is going on behind the operator's back.

Operators who are not accustomed to stopwatch studies are apt to imagine all sorts of things. Some will believe that the analyst is continually operating the stopwatch and collecting information on all workers within the range of vision.

Whenever a worker is being timed, the stopwatch should be in plain sight. Some analysts prefer the use of a special time study board with an attached bracket that holds the stopwatch. The bracket holder holds the watch securely but allows ease of operation. Carrying the watch on this type of board allows it to remain in plain sight of the worker and in convenient position for the analyst's use.

The analyst is dealing with facts and has nothing to hide. There is nothing in a correctly done stopwatch time study procedure that should be considered anything but fair by anyone who understands it. When time study work is properly handled, in cases where the correctness of a time study value is questioned, the analyst should willingly conduct a check time study in a sincere effort to settle the question with fairness to all concerned.

SELECTING THE ELEMENTS

For time study purposes, the work performed by the operator is divided into elements. An element is a distinct constituent part of a specific activity or task. It can be made up of one or more fundamental motions and/or machine or process activities selected for convenience of observation and timing.

Advantages of Time Studying Elements

Dividing the work into elements makes it possible to

- Rate performance more accurately.
- Determine changes in work elements or element sequences when checking standards in the future.

- Develop standard time values for frequently recurring elements. These elements can be checked against existing data, which helps maintain consistency.
- Identify nonproductive work.

Defining the Elements

Elements should be clearly defined. Preferably the element description should indicate the beginning point, the specific work included, and the ending point. The basic rules for selecting elements are

- Start and end each element with easily detected end points such as a definite sound or movement.
- The elements, depending on the need for detail, should be as small as is convenient to time.
- Time units of 0.03 to 0.04 minute are usually considered the minimum time for reading sweep hand stopwatches. Digital displays are somewhat easier to read, and minimum times of 0.01 to 0.03 minute are realistic. The skill and reflexes of the analyst also need to be considered in selecting the minimum time to be used.
- The elements should be as coordinated as possible. Elements should consist of a pattern of motions performed in sequence on a single object.
- Preferably an element should cover motions for only one object.
- Manual and machine times should be separate elements.
- Irregular and foreign elements should be separate from repetitive elements.

Several types of elements are usually found in a time study. Each time is handled differently in computing the standard and in developing standard time data. The types of elements are as follows:

- Regular—occur in every cycle.
- Irregular—do not occur in every cycle, but may occur at regular or irregular intervals, such as stock up or put away. Frequencies should be shown. As an example: stock up—every 100 parts, put away—end of work order, and so on.
- Foreign—not a necessary part of the work. These cover items such as errors and idle.

The skilled stopwatch analyst plans ahead. Often, if the time studies are arranged in spreadsheet formats, additional rates can be set and/or validated by interpolating. It is desirable to classify the work elements as constant or variable.

- Constant—time for the element does not vary significantly between jobs in the same class of work.
- Variable—time varies with some characteristic of the product, equipment, or process (such as weight, size, or material) within the same class of work.

For example, the time to start up a computer for word processing is a constant, regardless of the length of the letter. But the time to type the letter is a variable that depends on the format and length of the letter. Measurement of the length of the letter may be in general terms, such as the number of lines. But if the volume of typing is large, it may be desirable to measure the length of the letter more precisely, such as the number of characters (letters plus spaces and numbers plus spaces) and the format of the letter (the number of indents).

Minimum and Maximum Lengths for Elements

There are no hard-and-fast rules, just commonsense concepts, on how long or how short the time lengths for a stopwatch element should be. The work elements and the length of the elements should be

1. *Easily detected with definite end points:* It helps if the observer can hear the end point as well as see it. This could be a noise caused by laying a part aside or starting or stopping a machine, by flashing a light, or by a readily observed difference in the operator's movements.
2. *As short as is convenient to time:* Rule of thumb is usually 0.02 to 0.03 minute. The observer is apt to have difficulty observing and recording times shorter than these, unless the observer's reaction times are quicker than average. The type of stopwatch used will also affect the minimum time that is practical. See the previous section, Comparison of Sweep Hand and Digital Watches.
3. *As unified as possible:* The element descriptions and watch readings are simplified when the work performed in an element is uniform in motions and sequence. Maximum length of time can be very long where the element consists of the same work performed over and over again. The actual time spent reading the watch for a long element of uniform motions can be greatly reduced. The total time for the element can be calculated by correctly identifying the initial work content and number of times it is performed. Automatic drilling or doing computer calculations provide typical examples where all the work performed (between starting and stopping the machine) may be the same time duration. Where there are a number of variable work patterns in an element, it is best to subdivide the work element by uniform work patterns used within that element. The first rule of good time study is that the time values can be assigned to specific work sequences and methods descriptions.

Observation Principles

The following principles should be followed in making a time study.

Manual and machine times should be recorded separately. Where manual and machine times are performed simultaneously, manual times should be separate from machine times. Also, if two or more operators are working together, the elements should be divided according to the break between their simultaneous times and their nonsimultaneous times.

Regular and irregular elements should be recorded separately. There should be few, if any, variations in sequence of regular elements. By their nature, irregular elements often vary in sequence and occurrence.

Operators should follow agreed to work sequences. When the analyst, line supervisor, and operator have established the work sequence, the operator should follow it. Departure from the regular order interferes with the recording of the watch reading and complicates the study. Several alternatives are available. The observer can skip that cycle. This is why it is an advantage to use a form with more than 10 columns for recording cycles. Or the observer can continue to record the times per elements, coding the elements to show the sequence for that particular cycle. Or the observer and the line supervisor can decide whether the operator should be replaced by one who will follow the established sequence.

Irregular or foreign elements may be a necessary part of the work or may be completely unnecessary. For example, where the operator is required to get new material or supplies or orders, this can be necessary for the performance of the job. However, it may be difficult to determine if it is necessary or unnecessary. (For example, stopping work to talk to a fellow employee may be necessary or unnecessary. Don't guess; find out.)

Unnecessary irregular or foreign element occurrences should be duly recorded but should not be included in the standard for the job. Indicate the occurrence of an interruption on the time study by inserting a letter symbol opposite the time. Preferably these letter symbols have been preselected before the timing, so the observer will lose minimum time in jotting down the reason as well as the time observed.

OBSERVING THE OPERATIONS

Element Description

The first step in making observations is to subdivide the operation into a number of smaller operations that will be studied and timed separately. These subdivisions are known as *elements* or *elemental operations.* An element is a subdivision of an operation that is distinct and measurable; it contains a logical portion of the work.

An element, to be usable, must meet all the qualifications stated in the definition. For example, the element description "Move piece to vise" is neither distinct nor does it contain a logical portion of the work. In this example, the end point of the element is indefinite. At what point over the vise does the element end? This point can vary in the eyes of the individual observer, as well as being indefinite in the eyes of other observers. A more acceptable element would be "Move piece and place in vise." In this case, the end point of the element is definite. The element ends when the piece is in the vise.

Many companies develop a list of standard elements that are completely described. In such companies, the standard description of the element "Move piece and place in vise" might be: "The element begins as the operator grasps the part to be moved to the vise with one or both hands, depending on size, shape, and weight. It includes the total time required to move the part to the vise and insert it between the vise jaws, and ends as the part is located between the vise jaws."

With standard element descriptions of this type available to all the time study observers in the company, a consistency is obtained in all time studies that contain the standard elements. Data collected in such a manner are readily usable in developing standard data and making comparisons and in checking the variables.

When the element breakdown has been completed for a study, a short description of each element is recorded on the front of the time study form in the space provided. A more complete description of the elements is recorded on the back of the time study form in the Elements column.

Number of Observations

Many businesses have, through either company policy or labor contracts, established the number of cycles to be studied or have specified a minimum elapsed time for the study. There are also mathematical methods for determining the number of observations that must be made to determine time at a desired confidence level. Nomographs and equations have been developed to aid in determining the number of observations to be made. Most time study books provide the equations and/or nomographs for the statistical calculations. However, statistical rules cannot take into account all the factors that affect the study. The most important factor is the degree of variability in the time values between the different cycle readings.

The best practical guide to the number of observations required is obtained by charting the element times. Out of 10 cycles, a reasonable number of the time values for an element should be grouped together. Plot the time values from minimum time to maximum time, grouping the observed times in 5 to 10 percent ranges. The time values should follow a normal distribution, with one or two at the low end and one or two at the top end and with five to seven grouped together in the middle. This would be indicative of a normal distribution from observing 10 cycles for an element. If histograms for your elements follow normal distribution charts, it is reasonable to assume the number of observations is adequate.

However, suppose the time observed had a flat distribution, with one to three time values at a very low time and one to three at a very high time, and the balance of the studies scattered somewhat irregularly in between. This would indicate that the operator is following a number of different methods or is deliberately trying to confuse the analyst. Probably the best thing under these circumstances is to time study another operator.

Performance Rating

Performance rating is invariably required when setting standards by stopwatch time study. The objective of a time standard is to show the amount of time required to accomplish a unit of work, following a specified method, when working at the desired performance pace. Seldom in actual practice will these given conditions be universally observed.

- The operator being observed may work faster than average (naturally quicker, showing off, or speeding up due to nervousness from being studied).
- The operator being observed may work more slowly than the average (just naturally slower, slowing down on purpose to confuse the time study analyst, or excessive interruptions, and so on).

Some companies allow time studies to be made without performance rating or leveling, on the assumption that it is not necessary. Every audit we have made of standards at companies that do not use performance rating for stopwatch studies shows a tremendous inconsistency in standards. Also, most of their standards are considerably lower (read that "looser") than that company's desired performance concept.

Some performance leveling systems try to encompass a wide variety of factors in their performance leveling. These factors include skill, interruptions, operator speed, and working conditions. The customary yardstick for good performance leveling is a consistency of ±5 percent. While this may seem unusually liberal, in actual practice most time study people have trouble living up to that consistency goal. It is usually better to narrow down the number of variables considered in performance leveling and concentrate on rating operator performance.

Methods variables can be solved by asking the operator to follow the methods specified. "The methods specified should be that which the company expects employees to be able to follow to earn their pay scale." The working conditions can be best provided for by a job evaluation.

Performance Leveling Concepts

There are two different concepts associated with performance level:

1. Dedicated effort
2. Normal effort

Most of the original performance leveling concepts were related to dedicated effort. This is the time required by an operator following the specified method, working with dedicated skill and dedicated effort to accomplish the task.

Normal effort or average effort is often less than dedicated effort. Rule of thumb is that normal effort is 20 percent less than dedicated effort. Restated, average effort takes about 25 percent more time than dedicated effort.

This difference in average times supposedly reflects the stopwatch traditions that 25 percent more time will be taken by an average operator working under daywork conditions than the time taken by the same operator under incentive conditions.

H. B. Maynard was widely recognized for his technical contributions to stopwatch leveling, usually at average or daywork performance times. He very strongly influenced the predominant tendency today for using normal effort as the benchmark.

Currently, most performance rating concepts are based on average efforts. Most of the performance rating in the 1920s, 1930s, and 1940s was based on a concept of dedicated effort. There are advantages to both concepts.

Leveling films are available from Tampa Manufacturing, Bradenton, Louisiana; FAEHR Electronic Timers, Rockford, Illinois; Barnes Management Training Services, Ft. Lauderdale, Florida; Marvin Mundel, Silver Spring, Maryland.

Which Performance Level Is Best?

This decision depends on the management practices and concepts. The times are interchangeable.

- Adding 25 percent to required times equates to average times (or multiplying by 125 percent).
- Subtracting 20 percent from average time equates to required times (or multiplying by 80 percent).

Practicality of Average (Daywork) Time. It is easier to sell the standard, because it is easier to attain the standard. There is a psychological advantage in daywork operations in starting with motion-time values called *daywork* times. It sounds fair and reasonable, even though the resulting performance standards call for increased output over past averages.

Practicality of Required (Incentive) Time. On the other hand, there is also a psychological advantage in daywork operations in starting with required times and adding 25 percent. The 25 percent addition on the required time helps convince the supervisor and operator that the time standards are adequate, even generous.

Should Standards Be at Required Time, Even in Daywork Shops?

There is a tendency among some U.S. companies, and often among Japanese and other Far Eastern companies, to set the performance standards at required time—even for daywork operations. The reasoning: it is possible for the average experienced person, working with dedicated skill and effort, to do the work at required time. Managements who prefer required time standards identify the difference between performance at required time and performance at daywork time as waste. They believe that it is the responsibility of management to reduce that waste by better training, better scheduling, and better supervision.

USING THE STOPWATCH

Timing Methods

There are two different methods of operating a stopwatch during a time study.

1. Cumulative time or continuous (also known as split timing)
2. Snapback timing

In cumulative timing, the watch accumulates the time. Each reading shows total elapsed time from start of the first event. The watch is started at the beginning of the first element and is not stopped until the entire study is completed. The watch is read at the end of each element, without resetting, and the time value is recorded on the study sheet. Thus, the study sheet reflects only progressively larger watch readings. After the observations have been completed, the individual element times are calculated by a series of subtractions (to split the time per cycle into the individual element times).

In snapback timing, the watch is started at the beginning of the first element of the first cycle. At the end of each element, the watch shows the time for that element and is "snapbacked" to zero. This procedure is followed for each element throughout the study. It is a good habit in snapback studies to record the time at the start and end of the study.

The total of the element times and other activities noted in the study should add up to the total time from start of the study to the end. In practice, it tends to be somewhat less, owing to incorrect readings and missed elements. If there is significant difference, that time study is suspect.

Electronic timers are available (see Fig. 17.2.2 on digital watches) that record cumulative time and snapback time. This combination watch provides the advantages of both types (see Table 17.2.1).

TABLE 17.2.1 Comparison of Timing Methods

Cumulative	Snapback
Advantages:	Advantages:
Easy to teach	Good for irregular cycles
Gives accurate total performance time	Not hindered by delays
Employees more confident that all elements are included	Saves subtraction calculations
	Variations in element times readily apparent
Disadvantages:	Disadvantages:
Operator variations become confusing	More open to human error
Irregular elements become confusing	Operators and supervisors less confident that all elements are included
Delays become confusing	Operators and supervisors apt to be more accustomed to comparing cycle times than element times
More calculations, since subtraction is required to get the time for each element	
Variations in element times not readily apparent as the study is made	

Customary Stopwatch Calculations

There are many different time study forms. Most stock forms have space on the observation sheet for the following calculations (see Fig. 17.2.7 as an example).

The R and T Spaces. The R spaces are intended for posting cumulative watch Readings, with the watch running continuously throughout the study. After the observations are completed, the elapsed time intervals (T) are obtained by subtracting each reading from the next. The T values preferably should be in ink, or a different color from the R readings to avoid subsequent confusion.

If the observer chooses to use snapback readings, the elapsed times may be posted directly into the respective T spaces, leaving the R spaces blank; or the R spaces may be used for individual performance Ratings or for other notations.

Abnormal Times. Among the observed times for the same element over several cycles, some individual values may be considered abnormal for some reason, and accordingly are temporarily or permanently discarded. A line may be drawn through such a discarded value, but leaving the value readable for future reference.

Quantity Deviations. A circled number within the observation grid may be used to indicate a quantity of output, number of occurrences, or the like, which differs from the quantity implied in the element description. This special quantity will be considered in the subsequent calculations of elemental average.

Elemental Calculations. At the bottom of the sheet are lines for analyzing the elemental times. Across the bottom, the first line provides space for the Totals of the nondiscarded observed element times over several different cycles.

The second line provides space for the Number of Observations in the Totals.

The third line is for the arithmetic Average T, using the data from the first and second lines. This Average T is generally recommended as being the most valid indicator of the typical observed time for the element. However, some observers avoid calculating the average and

STOPWATCH TIME STUDY

simply arbitrarily select one of the observed values as being typical for the element, in which case the value on the third line would be the Selected T for the element.

Additional lines, for Minimum T and Maximum T, are sometimes provided for evaluating the timing and the leveling. Abnormally low minimum times or high maximum times need to be evaluated. Were they caused by mistakes in watch readings? Or were they due to undetected methods changes? Often very low or very high times are omitted from the calculations for Average T.

Letter (Adjective) Ratings. The Rating line is for companies using a multivariable rating system. It provides space for posting the "letters" indicating the various degrees of skill, speed, conditions, and rhythm, for any particular element which the observer considers should deserve a special performance rating different from the operator's overall performance during the study. If no significant performance deviations occur for individual elements, this line ordinarily is left blank.

Leveling (Rating) Factors. This line, Leveling Factor, is the sum of 1.00, plus the algebraic sum of the plus-or-minus leveling guide values selected from Table 17.2.2. This factor provides the numerical means for adjusting observed times toward a common standard level of performance. As implied earlier, many experienced observers avoid the check-off guides and directly estimate a rating factor. This rating may be for the overall time study, for the individual cycles, or for certain individual elements as well. The more frequent rating during a study tends to give more accurate results.

TABLE 17.2.2 Performance Rating Table for Leveling

Skill			Effort		
+0.15 +0.13	A1 A2	Superskill	+0.13 +0.12	A1 A2	Excessive
+0.11 +0.08	B1 B2	Excellent	+0.10 +0.08	B1 B2	Excellent
+0.06 +0.03	C1 C2	Good	+0.05 +0.02	C1 C2	Good
0.00	D	Average	0.00	D	Average
–0.05 –0.10	E1 E2	Fair	–0.04 –0.08	E1 E2	Fair
–0.16 –0.22	F1 F2	Poor	–0.12 –0.17	F1 F2	Poor

Source: S. M. Lowry, H. B. Maynard, and G. J. Stegemerten, *Time and Motion Study and Formulas for Wage Incentive,* 3rd ed., McGraw-Hill, New York, 1940, p. 233.

Leveled Time per Element. The next line, Element Base Time, is the time for the element average adjusted by the observer's estimate of the operator's level of performance. The result represents the observer's concept of a typical average time for the element, when performed as described and without interruption. This element base time ordinarily will be used for analysis and development of standard time data and/or sometimes for direct synthesis of the base time for the operation.

Elemental Times Distributed to Operation Cycles or Units of Output. The Occurrences per Unit space is used to indicate the number of times that the element is performed for each measured unit of output, which usually means for each completed cycle of the operation. For example, if a prescribed inspection occurs once on every fifth unit, the leveled time to perform one inspection is shown as Element Base Time; the fraction 1/5 is posted as Occurrence per Unit, to indicate that the frequency of occurrence is one in five. The occurrences per unit should be shown as a common fraction rather than as a decimal fraction. For example, if an element occurs 3 times in 10 units (or cycles), show the common fraction 3/10 rather than the decimal 0.3. Both fractions yield the same numerical result, but the decimal fraction does not clearly describe the actual observed frequency.

Occasionally identical elements will occur more than once in the cycle. Such elements customarily will be analyzed together to obtain a uniform (common) element base time. If such an element occurs twice per cycle, the Occurrence per Unit value would be 2. In most cases, however, the Occurrences per Unit will be 1.0.

Leveled Time per Unit. The Base Time per Unit for each element is the element base time multiplied by the occurrences per unit [9].

Stopwatches are available with built-in capability of being connected to PCs that do the tedious calculations and determine the standards. Sources include Royal J. Dossett, Excelsior, Minnesota; and FAEHR Electronic Timers, Rockford, Illinois.

MANAGERIAL ALLOWANCES ON LEVELED TIMES

Customary Allowances

Managerial allowances added to leveled time per unit include

- Daywork allowances
- Incentive allowances
- Personal, fatigue, and miscellaneous delay

PF&D Allowances

Personal, fatigue, and miscellaneous delay (PF&D) allowances are customarily used whether the performance rating concepts used are at required time or daywork time. Customary percentage allowances are as follows:

- Personal—3 to 5 percent
- Fatigue—3 to 5 percent
- Delay, miscellaneous—3 to 5 percent

This provides a total range of 9 to 15 percent. There are no firm rules or guidelines on the percentages, only habits and traditions. Usually the percentages are negotiated, based on past experience of the negotiating parties.

Rules of Thumb for Calculating PF&D

The following rules should be followed in calculating PF&D.

Personal allowances can be readily calculated. Take the number of rest breaks to derive the time to be allowed, and convert that into a percentage.

Miscellaneous delay can be done the same way. Usually miscellaneous delays of 6 minutes and over are recorded as time out or nonstandard time and not included in the production time. Accordingly, the only provision needed for miscellaneous delays in the standard time are the short interruptions of under 6 minutes. Theoretically, this is a small number per day; in practice, it is usually quite a few minutes per day.

Managers who prefer required time standards are also apt to consider miscellaneous delays as waste and consider the time lost as a managerial expense that can be eliminated by effective management practices.

Fatigue allowance is the only percentage that cannot be determined by observation. Numerous studies have been made without success in an effort to arrive at statistically sound conclusions as to fatigue allowances needed for average working conditions.

Special provision is needed for fatigue for excess discomfort due to extreme working conditions, or greater than average physical or visual effort. Provision for these conditions usually is made in the job evaluation plan or in work scheduling.

Another reason for an allowance for fatigue (even if not believed necessary) is that it provides additional minutes for miscellaneous delays. This is usually good, because no matter how carefully studies are made of miscellaneous delays, they tend to be underestimated.

General recommendation is that you use an allowance for all three as a combined percentage. In other words, if you decide to use 5-5-5, use a total of 15 percent. Do not break up the percentages into one amount for personal, one for fatigue, and one for delay. It is easier to verify that the total is adequate than to verify each percentage. Percentages 5 percent and under can be too readily disrupted by minor variations in the daily operations.

OVERCOMING GENERAL OBJECTIONS TO WORK MEASUREMENT

Everyone in the time study field is aware personally or through the experiences of others of the hostility toward work measurement by operators, by union leaders, by line supervisors, or by human relations personnel. Sociologists, expert consultants, union leadership, and company leadership have criticized the use of standards as damaging and deteriorating influences on human relations and employee productivity. Is this objection justified? Sad to say, many times it is.

Can the criticisms and the objections be overcome? Definitely. Overcoming the objections requires a combination of good standards, and thorough understanding by all who are involved in the standards program of the appropriate techniques for standards setting, for using standards, and for proper use of the standards.

The majority of the time, the first step toward better acceptance of work measurement is better standards. Do not expect good acceptance of your time standards if the time standards are not good. Consistency is an important criterion for good standards.

The next step for good acceptance of standards includes understanding of standards techniques and usage, plus proper use of standards.

1. It is undesirable to explain the standards techniques if the standards techniques are faulty.
2. It is irrelevant to understand how to use standards when good standards are not available.

The first step, therefore, is to verify or validate that the standards are correct. This should be done first by the time study analyst. Then when the analyst has verified that the standards are consistent, they need to be verified by the line supervisor and the operator.

Verification by the Time Study Analyst

There is nothing wrong with making mistakes. The big problem is when the mistakes are not caught by the analyst before somebody else finds them. The best thing a time study analyst can do to maintain credibility and build rapport is to double-check the time study results before the standards are issued. There are several easy steps to catch time study mistakes. The most common and the biggest mistakes in time study are in (1) faulty methods and (2) errors in performance rating.

Methods Verification. Methods errors tend to cause the biggest errors in standards. Methods errors are the easiest to find. Review the method used in your time study one more time. Does it still agree with the method being used by the operator? If not, correct the methods specified in the time study.

The second methods verification step by the time study analyst duplicates the verification step for line supervisors and operators: Review the method used in the time study with (1) the line supervisor's opinion of how the job should run, and (2) the operator's knowledge of how the job should run. Note: Be careful that the operator is not listening while the supervisor assesses the methods review, or the operator may merely mimic the line supervisor.

Performance Rating Verification. Verifying performance rating can be either easy or tough depending on the techniques used by the time study analyst. If histograms are prepared, clues are readily apparent as to the correct leveling percentages. Where the histograms follow a normal distribution curve, they offer good clues to proper leveling percentages for that study.

Where histograms have not been prepared or do not follow a normal distribution curve, the correctness of the time value for an element can be assessed if (1) it is an element similar to others time studied, and (2) a reference system is available so that comparable elements from other studies can be retrieved. If there is good comparison, with acceptable time studies of the comparable elements, the analyst can have reasonable assurance that the current time study and the performance rating are correct.

If the elements have not been cataloged and filed so that this verification can be done readily, an alternative is to prepare a spreadsheet of time studies by families of parts and see if the spreadsheet comparisons show logical similarities or progressions.

Validating the Performance Rating. The correctness of the performance rating time standard can also be checked by counting the pieces produced while watching the operator. Multiply the allowed time by the number of pieces completed. Divide this figure by the elapsed time. The resulting percentage will give the average performance of the operator, unless many or long foreign elements were included in the study. If this percentage parallels the performance rating that was used, it is probable that the performance rating was acceptable.

Verification by Line Supervisors and Operators

The first step for verification with line supervisors and with operators is to help them check for the reasonableness of the time study standard by reviewing it element by element. Where elements are comparable with other time studies, both line supervisor and operator can more quickly agree that the time study is correct for that element. It is usually easier to get agreement on individual elements than it is on overall times.

When verification of the elements shows they are reasonably correct, then is the time to validate the total time. This can be more difficult than for the element times. The opportunities for random variations in methods, parts, interference, performance, and the like can occur without being observed, unless there is very close attention through the entire cycle. This can be difficult to achieve, especially if the cycle is 10 to 15 minutes or longer. However, it is essential. The operator and the line supervisor may agree on the individual elements and still not be convinced without actual proof. At that time, it is necessary that both the line supervisor and the time study analyst stay with the operator when the operator is validating the standard time by doing the work. In the final analysis, only actual work counts.

But do your preliminaries first so that your final check can be as successful as possible. Usually, actual performance working diligently, under close knowledgeable supervision, will come within ±5 percent of the leveled time study.

Validation by Following Up on Results

If the operator on a job is failing to achieve the standard, do the following conditions exist:

- Material difficulties?
- Material-handling problems?

- Machine or equipment problems?
- Quality problems?
- Unfavorable attitude as evidenced by faulty performance on that job?
- Unfavorable attitude or unqualified operator, as evidenced by below par performance on other jobs?
- Diligence? Is the effort applied by the operator acceptable? If not, have the line supervisor provide someone who is willing to do the work with acceptable effort and correct methods.
- Job aptitude? Does the job require better skills or coordination than the operator brings to the task?
- Job knowledge? Does the operator have the required skill and talent to do the job, but is not following or has not been trained in the correct methods?

The time study standard is supposed to be correct for an operator working with good skill and effort, following the prescribed method, producing quality product from quality material. The standard should be validated in accordance with those specifications.

Use of Time Study Standards

Once the reasonableness of the time study standard has been validated, the standards can become viable tools. The first step to get good productivity is to use the standards positively. Employees want (1) personal recognition and (2) fair treatment consistent with the rest of their peer group.

They want to know what is a good day's performance. They want to be praised for good performance. They do not want to be criticized. Practicing this basic tenet of good management—"praise first"—has contributed strongly to increased acceptance of good work measurement standards.

Overcoming Supervisors' Objections to Work Measurement

Two important steps can improve the acceptance and use of work measurement from the supervisor's point of view:

1. Do measure the supervisor by the cost standards.
2. Do not measure the supervisor by the productivity standards.

One of the common burdens for the time study analyst is the hostility and opposition of line supervisors. This hostility and opposition by frontline managers is logical and to be expected in most operations. Why?

- Usually installing standards calls for increased output for the supervisor's work area and more work for the supervisor—in training operators, in having everything the operator needs on hand, in being sure everything is in good working order, and so on.
- This is particularly annoying when the standards ask for more output in an inconsistent pattern compared with historical output. And where the supervisors cannot understand how the standards were set, there is a fear and suspicion that unfair standards are being installed.
- Most frontline supervisors, where work measurement exists, are measured by their department's performance against time standards. Reducing the time standards coverage decreases the supervisor's workload. Increasing the time standards coverage increases the workload.

When operators are measured by time standards and line supervision and staff are measured by standard costs, there will be greater cooperation on good time standards along with mutual effort to reduce costs.

Management, aided by accounting and industrial engineering, must coordinate the standard time system and the standard cost system. Computer improvement in information gathering will permit appropriate cost information to be furnished quickly to management, line supervisors, and engineers.

Alert management will use bottom-line labor costs as a measurement of the effectiveness of both supervisor and engineer. When this is done, the work measurement engineer's job can be more enjoyable and more effective.

Recording and Filing

The time standard, as determined by the time study, is recorded on the routing sheet, manufacturing information sheet, and other permanent papers related to the operation. The time study itself is placed on a permanent file and is available for reference at all times.

Record Maintenance. Record maintenance preferably is simple and direct. There are a few practices that assist in good maintenance of time study standards. Finalize the time study—record the dates, job numbers, and the like. Be sure that all the blanks on the time study form have been filled in. Be sure of the time study calculations and then recheck. It is usually best to let somebody else recheck the calculations. It is human tendency to repeat mathematical mistakes.

Have the time study and standard been approved according to accepted practice? Approval varies from company to company: typically from the chief industrial engineer, the line supervisor, and the department head.

Copies of approved methods and standards should be distributed to all parties concerned: line supervisor (for attaching to machine or workplace), department file, design engineering, production planning and scheduling, the accounting department, industrial engineering department, or central file as called for by company practice.

Where company practice calls for a review of a standard on a periodic basis (1 year, 2 years, 5 years) a follow-up file should be established for that particular month of review. It can be as easy but cumbersome as filing an extra set of the study in a follow-up calendar file or simply by entering the part number, time study number, and date of study into a computerized update list.

TIME STUDY MANUAL

Every time study department should have a time study manual that sets forth the policies, procedures, and rules for the use of time study at that company. Advantage should be taken of every opportunity to explain the contents of the manual to all concerned. Time study has nothing to hide. The better this is understood, the more harmonious will be the relationships among time study engineers, supervisors, and the workforce. The time study manual can be as brief as copies of good studies, or can be a complete write-up of approved company practices and policies.

We have found it best to start out with an outline manual and add instructions and practices as time progresses so that the manual fits your particular operations. This can be done by support personnel using any type of word processing program. The data can be stored on a floppy disk and updated when necessary.

What should be in the manual? At minimum there should be copies of the forms to be used, the performance leveling procedures to be used (required time or daywork time), gen-

STOPWATCH TIME STUDY

eral practices on PF&D allowances, plus incentive allowances or measured daywork allowances.

It is important that the time standards practices are not cast in stone. As time progresses, changes in company operations, industry practices, and time study techniques may warrant a change. Many a company, by issuing strict rules instead of general recommendations, has hampered its ability to improve as conditions change.

An important caveat: Do *not* make your company time study manual part of a union contract. The company policy on work measurement can be adequately defined in the contract by stating (1) what the performance leveling concepts are, (2) that time standards will be set by generally accepted standards techniques, and (3) that the correctness of the standards can be verified by those techniques or other generally accepted techniques.

A union contract is best kept simple and focused on objectives. A time study manual dedicated to the objectives of the union contract but with provision for change as conditions change is most apt to keep your time study standards effective tools for setting consistent standards, increasing productivity, improving methods, helping to train operators, and reducing costs.

CONCLUSION

This chapter has reviewed the basic principles and practices for setting fair, consistent stopwatch standards. It is extremely important—to the company, to the employee, to you—that this be done fairly and consistently. Doing the methods work and performance evaluation that are required in time study provides practical skill and knowledge that will serve you well in any occupation. Do the job well, for both your immediate satisfaction and your personal growth.

Do read some of the reference books listed in Further Reading. The management books will enhance your knowledge of how standards play a vital role in industry. The time study books will provide additional insight into effective stopwatch studies. The list includes both current publications and some of the older ones. Read some of the old ones, if you can find them, to give you an understanding of the differences and the consistencies in practices over 70 years, from the early 1920s through the end of the 1990s. Royal Dossett is generally recognized as today's leading authority on time study, while Benjamin Niebel, Gerald Nadler, and Marvin E. Mundel are usually recognized as the leading authorities of the 1980s. Ralph Barnes in the 1960s and Lowry, Maynard, and Stegemerten in the 1940s were the recognized leaders. William Lichtner's book was published in the 1920s. His practical advice on the human relations aspects of time study coincides with today's concepts, even though there have been tremendous changes in technology and techniques.

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Clifford N. Sellie is chairman and founder of Standards International, Inc. A former faculty member of the University of Minnesota, Sellie holds a B.A. from St. Olaf College and an M.A. from the University of Minnesota. He is a registered Professional Engineer, State of Illinois, past president of the Industrial Management Society, and a senior member of the Institute of Industrial Engineers and the Society of American Value Engineers. Sellie founded Standards International, Inc., in 1948, to specialize in work measurement and work simplification. That firm became the largest U.S. industrial engineering firm, serving clients in the United States, Canada, Mexico, Germany, England, and Taiwan. He is listed in *Who's Who in Commerce and Industry,* and *World Who's Who in Industry,* received Industrial Engineering Institute's Phil Carroll Award for Outstanding Achievement in Work Measurement and Methods Engineering, and holds patents for Time-Motion Calculator (1970), Digital Electronic Timer (1995), and Computer Assisted Time Study System (1996).

CHAPTER 17.3

WORK SAMPLING AND GROUP TIMING TECHNIQUE

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Work sampling is based on the law of probability. It works because a smaller number of chance occurrences tends to follow the same distribution pattern that a larger number produces. Random work sampling and group timing technique (GTT), a fixed short-interval work sampling procedure, are both employed for work measurement and cost reduction analysis. These techniques can often replace traditional stopwatch time study, providing equal or better data at a lower cost.

BACKGROUND

Work sampling was introduced in England by a statistician, L. H. C. Tippett [1]. Its application was first applied to direct factory labor. Later it was employed to determine time utilization of office workers, teachers, management, as well as downtime and uptime of machines, material-handling equipment, and elevators. In the May 1953 issue of *Time and Motion Study* published in London, England, [2] Tippett reviews his experience:

> Round about 1927, I was making surveys in weaving sheds to discover the causes and durations of loom stoppages with a view to estimating how much of the productive capacity was lost for various causes. At first I used the obvious method of timing looms for long periods with a stopwatch. This caused no difficulty from the operators. No one thought of my activity as having any connection with time study as conventionally understood. The work was tedious, as it was practical to record only two, or three, or four looms at a time. I had to move about the shed and observe many looms to determine a reasonably reliable average.
>
> One day a weaving manager remarked: "I can tell at a glance whether the weaving in the shed is good. If most of the weavers are bent over their looms mending warp breaks, weaving is bad; if the weavers are mostly watching running looms, weaving is good." In a moment "the penny dropped." It became clear to me that a snapshot of the state of the looms in a shed was taken at an instant. It occurred to me that in an instant of time there was an indication of the good or poor rate of production surrounding that instant. Likewise, losses or delays in production due to various causes could be determined.
>
> After a little thought, I decided that the proportion (or percentage) of looms snapped as running was equal to the percentage of time the looms ran, on the average, during that short interval,

> and thus estimated directly the loom running efficiency. Likewise, the percentage of looms snapped as being stopped for any given cause estimated directly the percentage of the time on the average looms were stopped for that cause surrounding the instant of observation. Thus was started the *snap reading method.* An observer progresses around a mill and as he or she comes to each loom he or she takes a snap reading of its state, whether working or stopped, and if stopped, the cause of the stop. In this way he/she collects several thousand snap readings, classifies them, and estimates the various percentages.

Tippett employed basically the same approach that we use today, except today we are using electronic data collectors and computers that have a broad selection of data collection frequencies. Work sampling has been increasingly applied in many areas that were not formally measured. Because his original paper is not available in most libraries and because many people interested in work sampling desire to study it, Ralph M. Barnes reproduced it with the permission of Tippett in his book on work sampling [3,4].

The technique was introduced in the United States by Robert Lee Morrow, professor at New York University, in 1941. He changed the name from a *snap reading method* to *ratio delay study* [5]. He concentrated on sampling various production delays to determine allowances in work measurement studies.

The author, along with Harry L. Waddell, the editor of *Factory Management and Maintenance,* coined the phrase *work sampling* in an article on the subject in 1952 [6, 7], following the popularity of *Work Simplification* by Allan H. Mogensen (originator of work simplification), which identified methods improvement. This name has remained popular; however, librarians and web site researchers may find articles employing other titles such as *ratio delay study, activity sampling, chance observation,* and *snap readings.* Work sampling is currently being used in many segments of society. Many universities, industries, and professional societies have conducted educational sessions on work sampling. More and more institutions and industries are using this broad-gauged tool of work measurement for cost reduction and labor cost budgeting. The techniques of work sampling and/or group timing technique have been used by private firms, hospitals, educational institutions, and government for improving individual and general efficiency. Among other areas, research has been focused on chance occurrence and behavioral patterns of engineers, managers, nurses, and clerical and faculty employees.

HOW TO PREPARE FOR A WORK SAMPLING STUDY

Communication is important in initiating work sampling. In nearly every organization, if there is any failure regarding sampling, it is in communication. Harold Smiddy, former vice president of General Electric, said, "A great deal could be accomplished if we would consider communication in the light of this simple TTTG four-word formula, "Talk To The Guys" or "Talk To The Girls."

Gain Acceptance of Work Sampling

Although work sampling may seem simple enough, many people will not believe that sampling methods can collect accurate information. Management might feel that the installation of work sampling is its prerogative and that it is not necessary to report to the union, or to those to be observed, just what this technique is all about. One of the greatest needs in establishing a work sampling study today is gaining acceptance of the program. In short, it is necessary to "Talk To The Guys."

To illustrate, a work sampling grievance received in one company follows.

> GRIEVANCE: The aggrieved and all our unit people are aroused and highly perturbed by the actions of the company in regard to the so-called survey now being conducted in the shops. The answer to the grievance in the first step was that only the facility was being checked. We say this is false. The checker in our shop on one occasion was running around going "nuts," not for the facility, but for the operator, when for quite a spell he was nowhere to be seen.

No matter what heading or title tags it—*industrial engineering, work samples, spying, brainwashing,* or whatever it is—it is a violation of our agreement. We request this survey be stopped at once.

> COMPANY ANSWER: In this grievance, the union is strenuously objecting to the random work sampling program instituted by management of various machine facilities. They contend that union employees are being subjected to undue pressure, harassment, intimidation, etc., by this type of observation.

As thoroughly explained during discussion, work sampling is a method of gathering data pertinent to manufacturing operations and is widely used by industries. Information gathered during this program will be used for the sole purpose of improving operating efficiencies, and in no way can this program be construed as a means of harassment, intimidation, or coercing of our employees.

We do not expect employees to conduct themselves during the course of this work sampling program in any other manner than is normally expected of them. Accordingly, there should be no cause for alarm. We do not agree that the program places any undue pressure on our employees. Accordingly, the request that this study be discontinued is not granted, and any alleged violation of the agreement is denied.

Just what happened here? The industrial engineer attempted to do a good job in this case, but his attempt failed. The approach that he used was to talk to the superintendent about the work sampling study. He then asked the superintendent to convey to the employees through the line of command that "a work sampling was to be made for the purpose of evaluating both the equipment and the personnel to determine how time was expended." As a consequence of this unfortunate experience, industrial engineers on later studies requested an opportunity to explain work sampling to each level of personnel. They talk to the guys directly, with the line organization members present. There must be complete understanding and confidence of the people who are concerned with the results of a work sampling study. After the studies have been completed, the supervision and those studied should be enlisted in improving the conditions that are pinpointed by the study.

Define the Problem

Determine exactly what information is required. It is usually well to make a preliminary survey—observe the operations for a day or two—to get a list of the operation elements. When the causes and amounts of downtime on a machine are sought, it will be necessary to define all the possible causes. It is much the same as the preparation for a time study.

Make an Observation Recording Form for the Job

The work sampling study form must be individually designed in each case. Its design will depend on the number of workstations or people to be observed and the classification of the activities from which data is desired. Figure 17.3.1 shows a typical observation record form that was designed for a study of draw-bench activities for the production of copper and brass tubing.

Study		Date		Observer	
Item	Bench No. A-24	Bench No. A-23	Bench No. A-22	Bench No. A-21	Total
Cycle	𝍸 𝍸 𝍷𝍷𝍷𝍷	𝍸 𝍸 𝍸 𝍸 𝍷	𝍸 𝍸 𝍸 𝍸 𝍷𝍷	𝍸 𝍸 𝍷𝍷𝍷𝍷	71
Set Up	𝍷	𝍷𝍷𝍷		𝍷	5
Not Operating	𝍸 𝍸 𝍷𝍷𝍷𝍷	𝍷𝍷𝍷		𝍸 𝍸 𝍷𝍷𝍷	30
Operator Absent			𝍷		1
Operator Idle			𝍷𝍷		2
Point - Heavy					0
Small					0
Bent		𝍷	𝍷		2
Jaws - Not Grabbing		𝍷			1
Not Releasing					0
Stock - Tangled			𝍷		1
Breaking			𝍷		1
Handling	𝍷𝍷	𝍷	𝍷𝍷	𝍷𝍷	7
Waiting - Crane	𝍷	𝍷			2
Stock	𝍷	𝍷		𝍷	3
Tail in Die					0
Threading Manually			𝍷		1
Hook Won't Engage					0
Tube Released					0
Guide Tube into Die					0
Maintenance		𝍷		𝍷	2
Adjusting Rods				𝍷	1
Checking Pins & Dies				𝍷	1
Clean Up	𝍷	𝍷	𝍷		3
Receive Instructions			𝍷𝍷		2
Total					136

FIGURE 17.3.1 Observation record form designed from study of draw-bench activities.

Select the Frequency of the Observation

Nature of the Operation. If it is a short-cycle, repetitive operation in which all the desired elements occur frequently, the observations can be spread out over a shorter period of time than for a nonrepetitive operation. If it is a nonrepetitive operation or one in which some elements occur infrequently, it is better to make more observations over a longer period of time. This improves the chance of getting all the details.

Physical Limits. If there is just one observer and a long route is necessary to make one round of observations, the observer will be able to make relatively few observations in a day. For instance, a study of maintenance crews by one observer would probably require a long route, which might require a total of 10 minutes to complete the trip. Since there are 480 minutes in an 8-hour day or 48 ten-minute trips, it would be well to plan on 20 or fewer trips per day.

Total Number of Observations Required and Time Limit. If 1600 observations are needed for desired accuracy, and there are only 10 working days to make them, it is evident that an average of 160 observations a day will be needed. Also, the number of observations for each trip and the time of the trip will determine the total working days to complete the study (see Accuracy and Precision of Work Sampling).

Determine Time of Trips, on a Random Basis

Making 20 random samplings, which follow no set pattern, is quite often difficult. The human mind has a tendency to follow a set pattern. The safest way is to use a table of random numbers converted to time of day. Many calculators and personal computers have programs to generate random numbers.

Sampling can be randomized by the day or within an hour. For example, 15 random samplings per hour could be observed (called stratified sampling), or 160 random samplings per day could be made, with certain hours having more observations than others. Randomness of observation is stressed to reduce sampling errors.

Estimate the Number of Observations That Will Be Needed

This information is needed to plan the frequency, number of observers, and length of the study. The number depends on how accurate the answers need to be. A larger number of observations provides greater accuracy. However, operations have a point beyond which greater accuracy of data is not worthwhile. Experience with work sampling and knowledge of the operation will enable the analyst to make a fair off-the-cuff estimate. As the study progresses, observers can check the results to see when they have enough observations. A simple control chart that signals the end is explained in a subsequent section. Also, there is a mathematical method of preestimating the number of observations needed to give the practical accuracy desired.

Evaluate Methods by Which Biased Readings May Be Reduced

It should be pointed out that the inefficient motions or elements of an operation would not necessarily show up through a work sampling study. In some instances, the operator may be working during the downtime of the machine when this work could be done during the machine operating cycle. The work sampling observation would indicate that the operator was working, but a more refined motion study would show that this work could be performed during the machine cycle time.

The question has often been raised whether an operator is affected by seeing an observer coming and then beginning to work. It may be true that a study is thrown off at the beginning because of this situation. However, it has been found through experience that as observers pass the operators daily over a sufficiently long period of time, this influence on the readings levels off.

Have a Session with the Observer or Observers

Prior to the start of the study, clearly define and discuss each element to be observed and recorded. This step is very important where two or more observers study the same operation. Without it, they may not be consistent in how they designate what they see.

Example of Work Sampling

As an example of work sampling, assume it is desired to find out how much time a selected machine operator spends on operations, setup, maintenance, and delay. Using the work sampling technique, the machine is visited a predetermined number of times a day or hour. Assume that 10 random samplings that follow no set pattern are wanted during the day. The safest way to accomplish this is to use a table of random numbers such as Table 17.3.1, assigning times to these numbers. The numbers must be arranged in sequence.

Assuming that the period in which the study will be made is from 8:00 A.M. until 5:00 P.M., not including the lunch period from 12:00 to 1:00 P.M. and two 10-minute rest breaks at 9:30

TABLE 17.3.1 Table of Random Numbers

03 47 43 73 86	36 96 47 36 61	46 98 63 71 62	33 26 16 80 45	60 11 14 10 95
97 74 24 67 62	42 81 14 57 20	42 53 32 37 32	27 07 36 07 51	24 51 79 89 73
16 76 62 27 66	56 50 26 71 07	32 90 79 78 53	13 55 38 58 59	88 97 54 14 10
12 56 85 99 26	96 96 68 27 31	05 03 72 93 15	57 12 10 14 21	88 26 49 81 76
55 59 56 35 64	38 54 82 46 22	31 62 43 09 90	06 18 44 32 53	23 83 01 30 30
16 22 77 94 39	49 54 43 54 82	17 37 93 23 78	87 35 20 96 43	84 26 34 91 64
84 42 17 53 31	57 24 55 06 88	77 04 74 47 67	21 76 33 50 25	83 92 12 06 76
63 01 63 78 59	16 95 55 67 19	98 10 50 71 75	12 86 73 58 07	44 39 52 38 79
33 21 12 34 29	78 64 56 07 82	52 42 07 44 38	15 51 00 13 42	99 66 02 79 54
57 60 86 32 44	09 47 27 96 54	49 17 46 09 62	90 52 84 77 27	08 02 73 43 28
18 18 07 92 46	44 17 16 58 09	79 83 86 19 62	06 76 50 03 10	55 23 64 05 05
26 62 38 97 75	84 16 07 44 99	83 11 46 32 24	20 14 85 88 45	10 93 72 88 71
23 42 40 64 74	82 97 77 77 81	07 45 32 14 08	32 98 94 07 72	93 85 79 10 75
52 36 28 19 95	50 92 26 11 97	00 56 76 31 38	80 22 02 53 53	86 60 42 04 53
37 85 94 35 12	83 39 50 08 30	42 34 07 96 88	54 42 06 87 98	35 85 29 48 39
70 29 17 12 13	40 33 20 38 26	13 89 51 03 74	17 76 37 13 04	07 74 21 19 30
56 62 18 37 35	96 83 50 87 75	97 12 25 93 47	70 33 24 03 54	97 77 46 44 80
99 49 57 22 77	88 42 95 45 72	16 64 36 16 00	04 43 18 66 79	94 77 24 21 90
16 08 15 04 72	33 27 14 34 09	45 59 34 68 49	12 72 07 34 45	99 27 72 95 14
31 16 93 32 43	50 27 89 87 19	20 15 37 00 49	52 85 66 60 44	38 68 88 11 80
68 34 30 13 70	55 74 30 77 40	44 22 78 84 26	04 33 46 09 52	68 07 97 06 57
74 57 25 65 76	59 29 97 68 60	71 91 38 67 54	13 58 18 24 76	15 54 55 95 52
27 42 37 86 53	48 55 90 65 72	96 57 69 36 10	96 46 92 42 45	97 60 49 04 91
00 39 68 29 61	66 37 32 20 30	77 84 57 03 29	10 45 65 04 26	11 04 96 67 24
29 94 98 94 24	68 49 69 10 82	53 75 91 93 30	34 25 20 57 27	40 48 73 51 92
16 90 82 66 59	83 62 64 11 12	67 19 00 71 74	60 47 21 29 68	02 02 37 03 31
11 27 94 75 06	06 09 19 74 66	02 94 37 34 02	76 70 90 30 86	38 45 94 30 38
35 24 10 16 20	33 32 51 26 38	79 78 45 04 91	16 92 53 56 16	02 75 50 95 98
38 23 16 86 38	42 38 97 01 50	87 75 66 81 41	40 01 74 91 62	48 51 84 08 32
31 96 25 91 47	96 44 33 49 13	34 86 82 53 91	00 52 43 48 85	27 55 26 89 62
66 67 40 67 14	64 05 71 95 86	11 05 65 09 68	76 83 20 37 90	57 16 00 11 66
14 90 84 45 11	75 73 88 05 90	52 27 41 14 86	22 98 12 22 08	07 52 74 95 80
68 05 51 18 00	33 96 02 75 19	07 60 62 93 55	59 33 82 43 90	49 37 38 44 59
20 46 78 73 90	97 51 40 14 02	04 02 33 31 08	39 54 16 49 36	47 95 93 13 30
64 19 58 97 79	15 06 15 93 20	01 90 10 75 06	40 78 78 89 62	02 67 74 17 33
05 26 93 70 60	22 35 85 15 13	92 03 51 59 77	59 56 78 06 83	52 91 05 70 74
07 97 10 88 23	09 98 42 99 64	61 71 62 99 15	06 51 29 16 93	58 05 77 09 51
68 71 86 85 85	54 87 66 47 54	73 32 08 11 12	44 95 92 63 16	29 56 24 29 48
26 99 61 65 53	58 37 78 80 70	42 10 50 67 42	32 17 55 85 74	94 44 67 16 94
14 65 52 68 75	87 59 36 22 41	26 78 63 06 55	13 08 27 01 50	15 29 39 39 43
17 53 77 58 71	71 41 61 50 72	12 41 94 96 26	44 95 27 36 99	02 96 74 30 83
90 26 59 21 19	23 52 23 33 12	96 93 02 18 39	07 02 18 36 07	25 99 32 70 23
41 23 52 55 99	31 04 49 69 96	10 47 48 45 88	13 41 43 89 20	97 17 14 49 17
60 20 50 81 69	31 99 73 68 68	35 81 33 03 76	24 30 12 48 60	18 99 10 72 34
91 25 38 05 90	94 58 28 41 36	45 37 59 03 09	90 35 57 29 12	82 62 54 65 60

to 9:40 A.M. and 2:30 to 2:40 P.M., we have a total of 460 minutes, which may be divided into forty-six 10-minute periods. Time intervals of 10 minutes each, beginning with 8:00 A.M., 8:10, 8:20, and so on, will be numbered consecutively from 1 to 46. Analysts then make use of the random numbers by choosing as many as the number of observations they wish to make during the day. For example, ignoring numbers over 46 and duplicated numbers, the first 10 numbers may be 43, 24, 17, 12, 07, 38, 40, 28, 18, and 15. The numbers are then arranged in sequence and used to determine the time to start an observation trip. The element that is occurring at the instant of each visit is recorded. At the end of 10 days, the record may read:

Element	Observations	Percent of total	Minutes % × 460 minutes
Operation	60	60	276.0
Setup	18	18	82.8
Maintenance	10	10	46.0
Delay	12	12	55.2
	100	100	460.0

The percentage of distribution of the various elements, as they occurred during the example (100 observations), may or may not be enough. Usually a study would require considerably more observations, perhaps 5000 to 10,000 observations to obtain the degree of accuracy desired for the various causes of delays in the study. The number of elements in the study and the degree of accuracy desired for each element determines the extent of the study.

Over a sufficiently long study, the number of times an operator or machine is observed—idle, working, or in any other condition—tends to equal the percentage of time in that state. This is true whether the occurrences are very short or extremely long, regular or irregular, many or few. It should be emphasized that the study can be as detailed as one cares to make it, but the more detailed it is, the greater are the number of observations necessary to obtain the degree of accuracy that might be desired for all the elements.

The data yielded such as that shown previously is for the purpose of increasing operation time and reducing setup, maintenance, and delay time. After each work sampling study, improvement-brainstorming sessions with the people concerned is necessary. The fact that the study was made at all means that some decision was desired and considered necessary. The more detail planned for the study, the easier it will be after the study to determine possible refinements that will increase the critical added-value operation time. The objective is to optimize production by continuous improvement.

ACCURACY AND PRECISION OF WORK SAMPLING

Work sampling recognizes the variability inherent in work measurement. *Accuracy* is the measure of the degree of bias in measuring. *Bias* is the amount by which the long-run observed mean value of a set of measurements differs from the true value of the quantity. *Precision* is a measure of the reproducibility of the measured value of a given quantity without regard to the true value of that quantity.

Possible sources of bias are in

- The precise definition of the population to be sampled
- The ambiguity of the definition of various states of activity
- The latitude on the part of the observer in choosing the moment of observation
- The method of selecting the observation times

- The extent that the worker can anticipate the time of observation and is able to alter the state of activity that will be observed

During the design stage of the study, a period should be selected that will avoid some unusual circumstance. An example would be a major maintenance project that may occur once every five years. The period of study should be at least as long as the longest period of any cyclical behavior of the characteristic being studied. Likewise, the population on which the estimate is based must be similar to and representative of the period to which the estimate is to be applied.

The purpose of work sampling is to establish the value of p and q in the binomial Poisson distribution. The normal distribution describes the probabilities of the various values of p that might occur. It has a mean average of p. p is the percentage occurrence of any element selected, expressed as a decimal and $q = (1 - p)$ the remaining elements in the study. Usually the most important element is selected; the total of all the elements equals 1.

For example, in Fig. 17.3.1, the cycle time of the machine would be selected. The parameters of p and n (number of observations) are used in the binomial distribution, and p and σ in the normal distribution. However, the binomial values p and n are used to measure the parameter σ. The relation between p, n, and σ is given as the equation

$$\sigma_p = \sqrt{\frac{\hat{p}(1-\hat{p})}{n}}$$

$$\hat{p} = 0.522 \ (71 \div 136) \text{ observations}$$

$$1 - \hat{p} = 0.478$$

$$n = 136$$

$$\sigma_p = \sqrt{\frac{0.522(0.478)}{136}} = 0.0428$$

$1.96\ \sigma = 0.084$ at 95 percent confidence level; $\hat{p} = 0.522 \pm 0.084$.

Sigma (σ) is the standard deviation. The statistical derivation that shows that 68 percent of the time an observation can be expected not to deviate from the mean in the normal distribution by more than $\pm 1.0\ \sigma$ can also show the probability associated with more than $1.0\ \sigma$.

The percentage of the area under the normal curve z (see Table 17.3.2), or the selected level of confidence a, between a perpendicular erected at the arithmetic mean and a perpendicular erected at specific points to the left and right of the mean may be determined. The distance between the arithmetic mean and the selected point is expressed in terms of standard deviations as z.

TABLE 17.3.2 Selected Level of Confidence

z (+ and -)	a
1.000	0.68
1.645	0.90
1.960 (usually rounded to 2)	0.95
2.567	0.99

The formula to be used to solve for *n,* the number of observations required, is as follows:

$$n = \frac{z^2 p(1-p)}{\sigma^2}$$

Sigma is the standard error, arbitrarily determined. Therefore, as the standard error selected is decreased, the number of observations required is increased. For example, in Fig. 17.3.1, when $\sigma = 0.04$ instead of 0.0428 at 1.0 σ:

$$n = \frac{(1.0)^2(0.522)(0.478)}{(0.04)^2}$$

$$= 156 \text{ observations, rather than } 136$$

or at 1.96σ:

$$n = \frac{(1.96)^2(0.522)(0.478)}{(0.04)^2}$$

$$= 599 \text{ observations}$$

CONTROL CHART

The control chart, similar to those used in quality control, is advocated by many who apply work sampling to ascertain that the daily percent plots are within one-, two-, or three-sigma limits. This chart (Fig. 17.3.2) enables the work sampling observers to know that the data are in a state of statistical control and are homogenous and consistent. The control chart is considered pertinent in determining equitable delay allowances. It has an additional and important advantage in that the effect of a change in operating conditions can be checked to determine whether it produces a significant change in the percentage. As a consequence, the observer should be alert to strive to bring about greater control.

Control charts may be determined on a daily basis, using constant upper and lower control limits for *p.* The first few random trips of observations produce percentage *p*1, *p*2, *p*3, . . . , *pn,* or the average of *p.* This *p* is set up as the center line of the control chart. The upper and lower

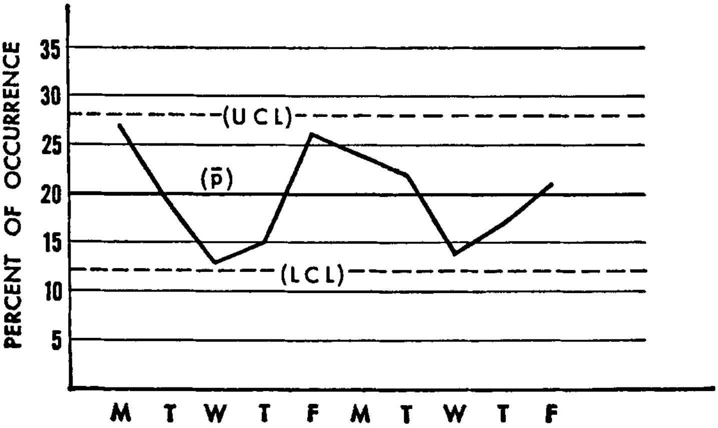

FIGURE 17.3.2 Control chart on a daily basis using constant upper- and lower-control limits.

control limits are the $p \pm 1\sigma, 2\sigma, 3\sigma$, depending on the confidence level desired. Also, these control charts are programmed into the electronic data collectors or computers.

EXAMPLE. If $p = 20$ percent and $n = 100$ observations per day, the upper-control limits (UCL) and lower-control limits (LCL) are

1 day—100 observations	10 days—1000 observations
$\sigma = \sqrt{\dfrac{p(1-p)}{n}}$	$\sigma = \sqrt{\dfrac{p(1-p)}{n}}$
$\sigma = \sqrt{\dfrac{0.20(0.80)}{100}}$	$\sigma = \sqrt{\dfrac{0.20(0.80)}{1000}}$
$= 0.04$	$= 0.0126$
$2\sigma = 0.08$	$2\sigma = 0.0252$
0.20 ± 0.08	0.20 ± 0.0252
$\pm 2\sigma = 12$ to 28%	$\pm 2\sigma = 17.48$ to 22.52%

Another approach to emphasize that the percentage of error reduces as the number of observations increases is to compute 2σ deviations on the cumulative number of daily observations (Fig. 17.3.3). Assuming 100 observations per day, 2σ is determined for 100, 200, 300 observations, and so on. This chart may also be used as an empirical method of determining the length of the study. When the variation from day to day is nearly level on a cumulative percentage for the element chosen to control the study, it can be assumed that enough observations have been gathered.

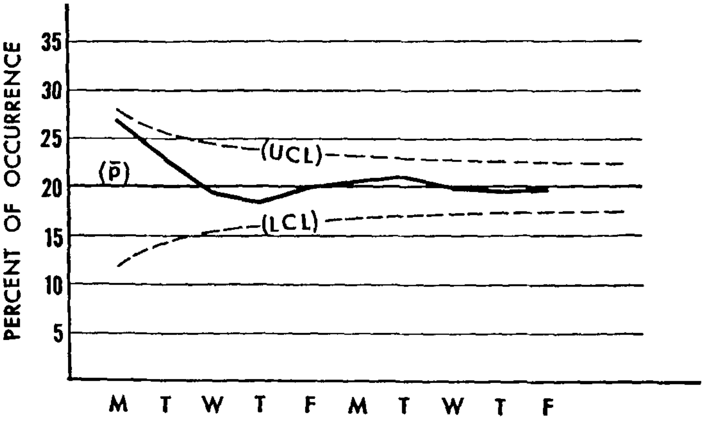

FIGURE 17.3.3 Control chart based on cumulative upper- and lower-control limits.

ELECTRONIC DEVICES

Datawriter

Handheld, battery-operated computers, specially made to collect data, are being used more frequently by industrial engineers. Royal Dossett [8] has developed one of these data collectors, the Datawriter, along with proprietary software called WorkSamp©. The Datawriter (Fig. 17.3.4) is about the size and weight of a TV remote. It has only a few large keys.

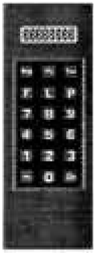

FIGURE 17.3.4 Datawriter.

Computerized sampling requires a code for each observation. It would be much like entering codes on your manual data form for each observation (see Table 17.3.3). The numbers 1110, 1210, 1325, and 1499 represent individual observations, equivalent to a tick mark. An observation comprises a four-digit subject/activity code. For example, observation 1325 indicates subject 13, activity 25—Pete (13) assisting someone (25). The codes are entered into a data collector. A time stamp can be recorded at the beginning of each tour. Time-stamping tours can be very beneficial. The basic procedure is to enter time to record the beginning time for a tour, then enter four-digit codes for each observed subject/activity on the tour.

TABLE 17.3.3 Example of Data Collection Study

	10 Work	25 Assist	97 Idle	99 Absent	Totals
11 Mary	1110				
12 Tom	1210				
13 Pete		1325			
14 Sally				1499	
Totals					

The data are downloaded to the computer. From the data, a computer program immediately develops whatever summaries are desired. The summary usually reports ratios, observed as percentages, that are the percent observed for each activity in the study. The percentages reveal the activities consuming the most time, indicating to management the tasks that would benefit most from improvement. The percentages also indicate bottlenecks and wasted time. Ratios or percentages can easily be converted into time. For example, if a study of 10 people performing similar activities took place over a three-week period (15 days), 150 labor-days were consumed, or 1200 labor-hours at eight hours per day. If an activity, such as waiting, showed as 12 percent, the company lost 144 labor-hours during the three weeks just on waiting, or about 2400 labor-hours over a 50-week (250 workday) year:

$$0.12 \times 10 \text{ people} \times 250 \text{ days/year} \times 8 \text{ hours} = 2400 \text{ labor-hours/year}$$

Time can similarly be calculated for the purposes of determining standard times for activities.

$$\text{Standard time} = \frac{\% \text{ of activity} \times \text{hours/workday} \times \text{days} \times \text{workers}}{\text{pieces}}$$

Assume that 10 people were typing letters. During the 15 days, the activity of typing letters required 50 percent of their time, and 1800 letters were typed during this period:

$$\text{Standard time} = \frac{0.50 \times 10 \text{ people}}{\text{period}} \times \frac{15 \text{ days}}{\text{person}} \times \frac{8 \text{ hours}}{\text{day}} \times \frac{1 \text{ period}}{1800 \text{ letters}}$$

$$= 0.333 \text{ hours/letter or } 20 \text{ min/letter}$$

Summary Reports. Summary reports can be formatted on the computer in any manner. A summary report can be printed of the entry data collected, showing percentage observed for each activity for the entire population. These reports are frequently formatted in a spreadsheet layout with activities along one axis and operators and machines along the other. The intersection of a row and column then supplies the percentage of time a given code was recorded. Summary rows and columns can be added along with other relevant data. Deviation can be calculated for each activity.

Time frame analysis is very useful in uncovering inefficiencies that occur only in the morning, early after lunch, on the second shift, or the day after a holiday, and so forth. Work sampling on a laptop computer offers the industrial engineer an excellent tool for every conceivable type of analysis.

National Nursing Home Restraint Minimization Project. William J. Foley [9] at Rensselaer Polytechnic Institute employed Datawriters in 16 nursing homes. The study is detailed in the following sections.

Study Objective. The objective of the study was to determine the change in patterns of work as measured by the time staff spent in a set of named activities that resulted from discontinuing the use of physical restraints. Data collection was done before restraint use was reduced and after its reduction, approximately two years later. Individual self-logging results were used to calculate the percent of responses recorded for each of the listed activities that was used as a proxy for the change in time spent on activities.

Data Collection Method. By recording the action of staff at random time intervals, the time that staff spent in a particular activity was measured. In self-logging work sampling, staff recorded their action in response to a prompt that occurred at randomly spaced intervals. The Datawriter is programmed to emit an audible prompt, a 1.5 second beep, at an average interval selected by the analyst. In this study, a 12-minute average interval, five prompts an hour, was applied. The project staff supervised work sampling at each nursing home in the pre- and postrecording periods.

An instruction sheet describing the keypad entries required of staff when the Datawriter beeped was mounted to the back of the Datawriter. The instruction sheet also defined with examples the categories in which the activity was engaged when the beep was heard.

Data Collection Steps. On hearing the beep, observers were instructed to record a two-digit code for the activity occurring when the beep sounded and to record the current time using the Time key on the keypad and the clock feature built into the Datawriter. Seven activities were defined as follows:

1. *Mobility assistance*—assisting resident with walking or wheeling
2. *Activities of daily living ADLs assistance*—assisting resident with ADLs other than mobility
3. *Floor duties*—duties not directly related to residents such as making beds
4. *Social interaction*—talking to resident unrelated to other activities
5. *Medications and treatment*—administering medications or technical care
6. *Direct monitoring*—watchful monitoring of resident(s) unrelated to other activities
7. *Nurse station activities*—charting, documentation, and staff supervision

The work sampling data collection lasted 24 hours on each nursing unit covering all shifts. The data collected identified the skill level of the staff person. Data was downloaded at the end of each shift and the Datawriter refreshed for the next user. Software was used to download data to a computer and to prepare reports of data results.

Observed Workload Changes. The seven tasks were placed into two groups of tasks to lower the dimensions involved in analysis and discussion: Direct Personal Care (direct care) and Technical, Hotel, and Administrative activities (technical care). Direct care included

- Time in mobility assistance
- ADL assistance
- Social interaction
- Direct monitoring

WORK SAMPLING AND GROUP TIMING TECHNIQUE

Technical activities were

- Medications and treatments
- Floor duties
- Nurse station activities

Pre- and postdata were presented in the same table for each facility. The work sampling study collected data with the staff type. There were big differences in patterns of time use among the staff types, as one would expect. Because of these differences, the full report presents and discusses results by skill level starting with nursing assistants. In this presentation, only the results for nursing assistants are presented.

Facility names were removed from the report. Facilities gave permission to report the work sampling in the evaluation report. However, permission beyond that was not explicitly obtained. Each facility was considered as a data point for calculating and presenting summary data. This was done because the change occurred at the facility level from the baseline in terms of the practice patterns and work patterns of staff. Each facility experienced a change from the old pattern of employing restraints to the new pattern when restraints were discontinued to the extent possible.

The data showed different patterns of utilization and activities of staff among facilities at each benchmark point, before and after restraints were discontinued to the extent possible. The direction of change—increase or decrease of direct care—in a facility was the area of interest. Focusing on the direct personal care activities, the nursing assistant staff for 13 of the 16 facilities experienced an increase in direct time with residents. The decrease in the other three facilities was in the low single digits, 2 to 4 percent, while the increases generally averaged 18 percent.

These increases in direct personal care (resident contact time activities) came from a reduction in technical and administration activities. The average of the change in each facility in this category was a 25 percent decrease. For nursing assistants, the data indicated that there was a major upward shift in their caregiving activities. They spent more time in direct personal care activities after restraints came off—more time caring for and in the presence of residents. The dependency level of residents decreased, thus this time was not just driven by the direct physical needs of residents.

The results translate to an increase of contact time by nursing assistants from 40.1 minutes per active working hour to 46.5 minutes. An active working hour is time outside of personal and break time. In an 8-hour work shift with a personal allowance factor of 12 percent the number of active working hours was 7 hours or 420 minutes. Extending this hourly observation to the shift basis, nursing assistants spent 44 more minutes in the direct care of residents per shift after restraints were removed.

Electronic Random Reminder

Divilbiss Electronics has developed the JD-7 Random Reminder, which provides signals with 21 different sampling rates. A vibrating signal notifies the observer to make the next mark on a work sampling form. Divilbiss has done much to encourage the use of this unit for work sampling studies.

Work measurement has often been viewed as an adversarial process. Management attempts to measure labor costs; employees, fearing a speedup, actively interfere with the measurements. It does not have to be that way. It is possible to design a time study that yields valuable management data and at the same time actually increases employee job satisfaction. The term *empowerment* may be an overworked buzzword, but in this instance it is probably the most appropriate single word description of the employee benefit.

Work Sampling as a Win-Win Management Tool. Rick Rutter of G.D. Searle & Company [10] describes the following study. The primary function of a pilot plant operation in a pharmaceutical company is to create test quantities of new compounds in quantities ranging from a few pounds to a few hundred pounds. A secondary function of the operation is to demonstrate that new compounds can be produced in commercially feasible ways. Several processes run simultaneously with each process involving approximately a half dozen steps. (In chemical parlance, a step is the making or breaking of a chemical bond.) As new and different processes enter the work stream, operators' assignments are adjusted, as well as the scheduling of equipment. Using observation, discussion, and intuition, a tentative activity list was created of the work activities of the operators. The list is shown in Table 17.3.4.

TABLE 17.3.4 Work Sampling Activity Data—Operations Department

No.	Activity	Nov.	Dec.	Jan.	Total	Percent
1	Operation	294	372	349	1015	40.3
2	Equipment cleaning	88	67	39	194	7.7
3	Run preparation	24	17	30	71	2.8
4	Documentation	23	17	48	88	3.5
5	Facility cleaning	31	30	5	66	2.6
6	Waste handling	10	6	10	26	1.0
7	Support activities	14	20	25	59	2.4
8	Training	53	25	26	104	4.1
9	Personal	113	107	122	342	13.6
10	Raw materials	40	16	36	92	3.7
11	Op. supplies	9	7	12	27	1.1
12	Continuous improvement	6	26	39	71	2.8
13	Eng. support	18	31	34	83	3.3
14	Op. systems	10	3	9	22	0.9
15	Waiting time	4	4	5	13	0.5
16	Operator comm.	67	44	65	176	7.0
17	Other	17	19	32	68	2.7
	Total samples	821	811	886	2518	100.0

The operators were given written descriptions of the activity categories, and questions were answered until everyone had a clear understanding of the activity categories. Operators also received simple data cards and Divilbiss Electronics Random Reminders. Each time they were signaled randomly, operators wrote down the numeric activity code for the activity in which they were engaged at the exact instant of the signal. Capturing data in this way had several clear advantages:

- No additional employees were needed to serve as observers.
- Operators know more accurately than an observer exactly what they are doing at the instant of the sampling signal.
- Making three or four sampling entries per shift is enormously easier for operators than keeping accurate, detailed diaries.
- A genuine random time sampling study is inherently more accurate than a detailed diary study.

WORK SAMPLING AND GROUP TIMING TECHNIQUE

One operator on each shift was responsible for collecting and tabulating the sampled data from all the operators on that shift. This was not much of a burden since the sampling rate chosen (0.4 hour/sample) generated only about 20 to 25 samples per shift.

Table 17.3.4 summarized the data collected over a three-month period and was created using nothing more than a pencil and a pocket calculator. The next step was not a traditional one, but it was the key to this being a win-win tool. Operators and management, working together, went through the table analyzing and discussing every activity by asking questions:

Was this activity taking too much time?

Should this activity be receiving more emphasis?

As an example, activity 5, facility cleaning, shows 61 samples for November and December. As a result of that data, janitorial support was added in December, which explains why the figure dropped so sharply in January.

Operators are an expensive resource, and there is always concern that they are being used effectively. The study served to reassure upper-level management that two potentially troublesome activities are not a problem at all. First, the amount of personal time taken, activity 9, was very low considering that this includes both lunch and scheduled breaks. And second, operators do not spend much time waiting, activity 15, because there is always a backlog of work to be done, there is no shortage of equipment, they are well trained, and they have the right attitude.

Operators supported the study enthusiastically, which brought about the following benefits:

- The involved employees applied their expertise to a more efficient system.
- By documenting what they did, they have increased their visibility and respect within the company.
- They now have a tool for justifying additional equipment (pumps, cleaning tools, automated controls, etc.) and support services (ventilation, janitorial, etc.).
- Decisions by consensus create teamwork and a high level of job satisfaction.

Any time study is a snapshot in time. The real benefit comes from doing studies and constantly asking the question, “Could we be running the operation better?”

GROUP TIMING TECHNIQUE

The group timing technique (GTT) was developed by George New [11]. Group timing technique is a very short fixed interval work sampling procedure for multiple activities that enables one observer to make a detailed elemental time study on 2 to 15 employees or machines at the same time. Continuous elemental observations are made at predetermined fixed intervals and are recorded as tallies on a form or within an electronic data collector listing the elements of the job. Elements that will vary in time because of operator performance may be leveled. However, many industrial engineers recognize that the average of the total observations of the various people observed will tend toward 100 percent. Therefore, rating is ignored.

The author, as well as many others, have employed work sampling on a random or fixed interval at a frequency of 5 minutes or longer. The same operation or operators may be observed every 1 minute, 3 minutes, or some other small fixed interval of time. Group timing technique is an efficient and versatile measuring procedure easily applied to work measurement and quantitative surveying of tasks in industry.

GTT can often replace traditional stopwatch time study, providing equal or better data at a lower cost. GTT is ideal for establishing standards for small group operations where all the workers are instantly visible to the observers, and the work elements are in the subminute to low-minute range. GTT, employing the Datawriter, is examined in the following sections.

In practice, a beeper is set to beep at fixed intervals (rather than random intervals)—for example, every 30 seconds. At the beep, the observer quickly records the activity of each worker performing similar work. At each interval, the current element being performed by each worker is quickly noted. At the end of the study, total observations for each element are multiplied by the mean decimal percentage, yielding time spent on each element.

The time was easily determined by multiplying the mean percentage for each of the elements by the total time of 150 labor-minutes for the study. Therefore, if 40 pieces were produced, the time per piece for each element is as shown:

	Minutes/40 pieces	Minutes/piece
Element 1	90	= 2.250
Element 2	20	= .500
Element 3	40	= 1.000
Total		3.750 minutes/piece

The 10 steps employed in making a GTT study as developed by Rolf Tiefenthal are listed here [12]:

1. Define purpose of the study.

2. Select the operation, group of operators, and time periods to be studied.

3. Decide whether to separate the time for each operator.

4. Decide on the recording method.

  a. By the observer(s)

  b. By the operator(s) making their own observations

  c. By memomotion filming

Using observers for recording is frequently the most suitable procedure since they can concentrate on the study. They register tallies on a study form, or employ an electronic data collector for subsequent data processing. The operators can make recordings if the study does not interfere too much with the work.

5. Define elements.

Preliminary observations should be made to determine what elements to include. At this time, it should also be decided how detailed the study needs to be. The number of elements should be minimized without jeopardizing the purpose of the study. Some open space should be left on the study for unexpected elements. The element breakdown should be logical and with natural limits easily definable and observable. It is best to develop a brief written element definition.

6. Design and reproduce study form.

GTT is used in so many varying situations that no standard form suitable for all purposes exists. A suitable form should be designed for each study. List all elements on one 8½-by-11 (A4) sheet if possible. The forms should be reproduced in a sufficient number to allow for summarizing the final results. In making the study, each observer will usually start a new form each hour.

7. Select interval size.

The proper interval size is primarily dependent on the number of operators or machines and their location. Observers should have time to observe thoughtfully what is happening. The interval, however, must be shorter than the smallest element to be measured.

8. Determine study periods and duration.

Several factors influence the length of the study. The minimum number of total observations for the critical activity should be computed to ensure that the data obtained are truly representative of normal conditions. The duration of the study must be sufficient to level out the natural, long-cycle variations that may exist in the process. Since GTT is a frequent fixed

WORK SAMPLING AND GROUP TIMING TECHNIQUE

short interval work sampling procedure, accuracy and precision are determined employing the Poisson distribution. Daily plotting on the control chart should be considered. This continuous check on the daily and accumulated values of one or more critical activities may be helpful in determining the stability of conditions and evaluating the necessary duration of the study.

9. Consider a trial study.

A brief trial study will provide a good test of the soundness of the element selection, element definition, and interval size.

10. Make the study.

Record carefully the names or numbers of the operations, operators, interval size, and other information. Record the starting time to the closest half minute. Change sheets at fixed intervals, such as every hour. Record the time for each switch on both the old and the new form. If desired, the performance rating for each operator is recorded on each sheet.

On a half- or all-day GTT study, account for the full four hours or eight hours of each employee. This may require elements such as start late, quit early, coffee break, safety meeting, work on foreign operation (element when operators temporarily perform some task that is not part of their jobs), or absent (reason unknown is often required; therefore strive to determine the reason). The piece count and other pertinent information must also be recorded, and the study should be concluded and summarized the same way as a time study. This will make the study more understandable, reduce errors, and make the study easier to summarize.

CONCLUSION

Random and fixed interval work sampling are convenient methods of studying worker and machine processes in industry and elsewhere. It is a tool of choice for nondirect and staff work measurement. The procedure is simple and easy to learn and can be partly automated if used extensively. Systematic process improvement is achieved by detailed data that may be subjected to other methods improvement techniques, such as a questioning attitude, time management, detailed motion study, value engineering, simulation, and the application of mathematical, statistical, or programming procedures.

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BIOGRAPHY

Chester L. Brisley, Ph.D., P.E. is a professor in the DeBusk School of Business at Lincoln Memorial University, Harrogate, Tennessee. He received his industrial engineering education from GMI Institute and Wayne State University. Brisley has been on the faculty of Marquette University, California Polytechnic State University, San Luis Obispo, California, and the University of Wisconsin-Milwaukee. He has been employed as a manager of management services with certified public accounting firm Deloitte Ross, New York, New York, and as an industrial engineering consultant at A.T. Kearney, Chicago, Illinois. He was an industrial engineering manager with a number of industries such as North American Aviation, Wolverine Tube, Chance Vought Aircraft, and Allis Chalmers. Brisley has been active in professional societies as an officer, and has received awards of recognition by the Institute of Industrial Engineers, the Methods Time Measurement Association, and the Society of Manufacturing Engineers.

CHAPTER 17.4

MOST® WORK MEASUREMENT SYSTEMS

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H. B. Maynard and Company, Inc.
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As with any measurement, the measurement of work brings knowledge. Through this knowledge, factual decisions and improvements can be made and could be exercised. Work measurement has for a long time been a sound management tool to be used as a basis for planning and scheduling, estimation of costs, and evaluation of performance. In essence, managers are looking at work measurement as a means to satisfy their desire and need to know, and predict with confidence.

Scientifically developed work measurement tools have been available to the industrial engineer since the late 1800s. A variety of such tools are now being used in a large variety of industries worldwide.

In search of accuracy, consistency, and speed, predetermined motion time systems were first being developed during the mid-1920s starting with motion time analysis (MTA). Methods time measurement (MTM), published in 1948, became the foundation for many simplified and more efficient techniques. One of the most recent MTM-based techniques that is easy to learn and fast to use is MOST work measurement systems.

This chapter will provide an overview of the concept and principles of MOST work measurement systems including BasicMOST, MiniMOST, and MaxiMOST. Several examples will illustrate the application of MOST for different activities.

INTRODUCTION

Because industrial engineers are trained to accept that with sufficient study any method can be improved, many efforts have been made to simplify the analyst's work measurement task. This has, for instance, led to a variety of work measurement systems now in use. These achievements also led to the examination of the whole concept of work measurement to find a better way for analysts to accomplish their mission. The result was the creation of a new approach to be known as the Maynard Operation Sequence Technique (MOST®). The concept of MOST was developed in 1967 and the complete BasicMOST system was first introduced in Sweden in 1972 and in the United States in 1974. The activity-based MOST system is considerably faster to use and easier to learn than motion-based and action-based systems. For these reasons, MOST is a user-

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friendly work predetermined motion time system. For information about other common work measurement systems see Chap. 5.1, Measurement of Work.

THE MOST CONCEPT

To most of us, work means exerting energy to accomplish a task or to perform a useful activity. In the study of physics, we learn that work is defined as the product of force times distance (W = f × d) or simply, work is the displacement of a mass or object. This definition applies quite well to the largest portion of the work accomplished every day, like pushing a pencil, lifting a heavy box, or moving the controls on a machine. Thought processes, or thinking time, is an exception to this concept, as no objects are being displaced. For the overwhelming majority of work, however, there is a common denominator from which work can be studied: the displacement of objects. All basic units of work are organized (or should be) for the purpose of accomplishing useful results by simply moving objects. That is what work is. *MOST is a system to measure work;* therefore, *MOST concentrates on the movement of objects.*

Work, then, is the movement of objects; maybe we should add, following a tactical production outline. Efficient, smooth, productive work is performed when the basic motion patterns are tactically arranged and smoothly choreographed (methods engineering). It was noticed that the movement of objects follows certain consistently repeating patterns, such as reach, grasp, move, and position the object. These patterns were identified and arranged as a sequence of events (or subactivities) manifesting the movement of an object. A model of this sequence is made and acts as a standard guide in analyzing the movement of an object. It was also noted that the actual motion content of the subactivities in that sequence varies independently of one another.

This concept provides the basis for the MOST sequence models. The primary work units are no longer basic motions like in methods time measurement (MTM), but fundamental activities (collections of basic motions) dealing with moving objects. These activities are described in terms of subactivities fixed in sequence. In other words, to move an object, a standard sequence of events occurs. Consequently, the basic pattern of an object's movement is described by a universal sequence model instead of an aggregate of detailed basic motions synthesized at random.

Objects can be moved in only one of two ways: either they are picked up and moved freely through space, or they are moved in contact with another surface. For example, a box can be picked up and carried from one end of a workbench to the other, or it can be pushed across the top of the workbench. For these two types of moves, a different sequence of events occurs; therefore, a separate MOST activity sequence model applies. The use of tools is analyzed through a separate activity sequence model that allows the analyst the opportunity to follow the movement of a hand tool through a standard sequence of events, which in fact, is a combination of the two basic sequence models.

Consequently, only three activity sequences are needed for describing manual work. The BasicMOST work measurement technique, therefore, comprises the following sequence models:

- *General Move Sequence*—for the spatial movement of an object freely through the air
- *Controlled Move Sequence*—for the movement of an object when it remains in contact with a surface or is attached to another object during the movement
- *Tool Use Sequence*—for the use of common hand tools
- *Manual Crane Sequence*—a fourth sequence model for the measurement of moving heavy objects by using, for instance, a jib crane is also part of the BasicMOST system, although used less frequently than the three first sequence models.

A MOST analysis is usually created by combining several sequence models, which will form either a suboperation (standard data unit) or a complete operation standard; therefore, the hierarchy of data basically includes these levels: activity sequences, suboperations, and operations. The terms used and their relationships in this hierarchy are shown in Fig. 17.4.1.

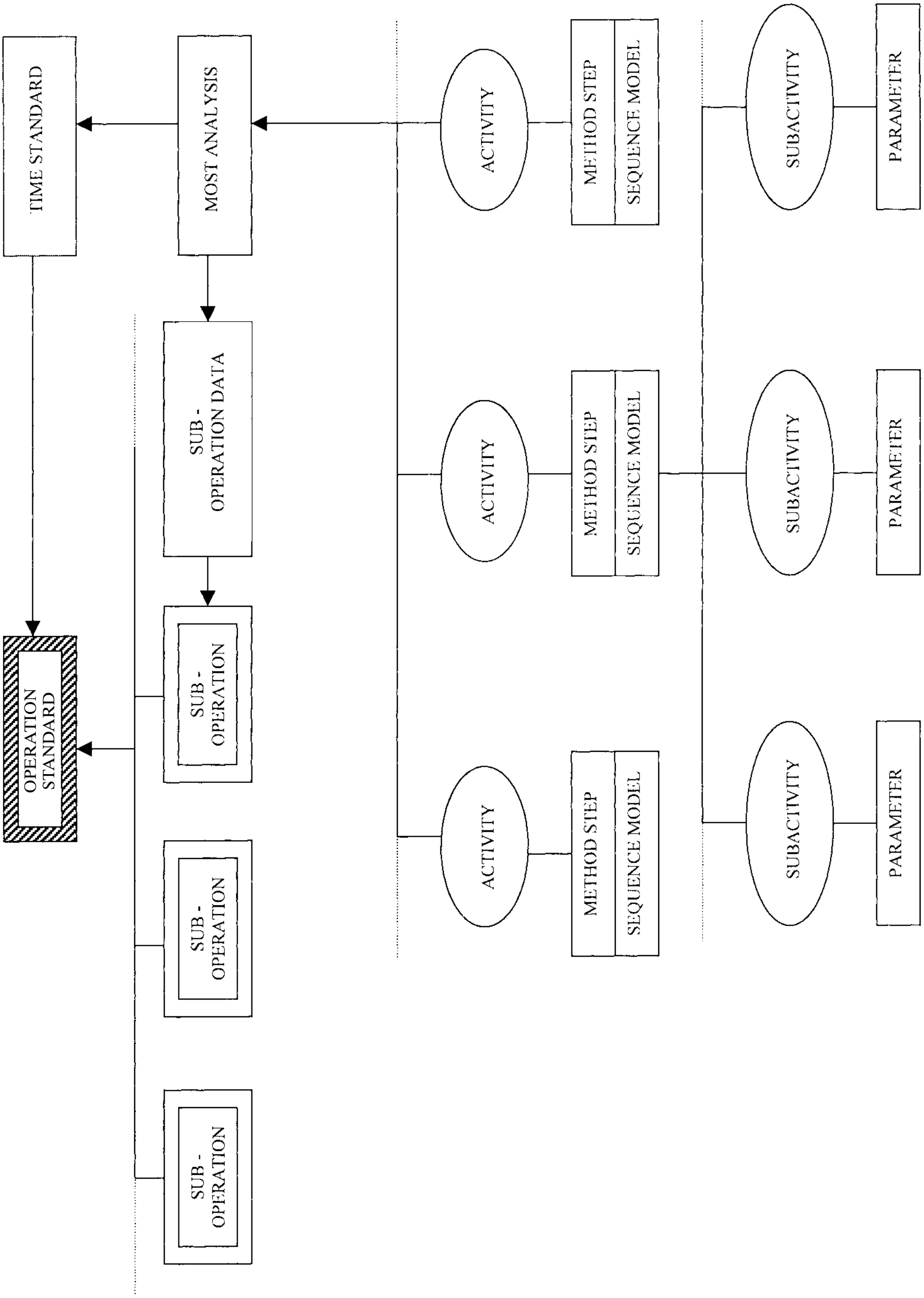

OPERATION STANDARD
TIME STANDARD
SUB - OPERATION
SUB - OPERATION
SUB - OPERATION
SUB - OPERATION DATA
MOST ANALYSIS
ACTIVITY
METHOD STEP
SEQUENCE MODEL
ACTIVITY
METHOD STEP
SEQUENCE MODEL
ACTIVITY
METHOD STEP
SEQUENCE MODEL
SUBACTIVITY
PARAMETER
SUBACTIVITY
PARAMETER
SUBACTIVITY
PARAMETER

FIGURE 17.4.1 Terms and their relationship in connection with a MOST analysis.

THE BASIC MOST WORK MEASUREMENT TECHNIQUE

Sequence Models

General Move is defined as moving objects manually from one location to another freely through the air. To account for the various ways in which a General Move can occur, the activity sequence is made up of four subactivities:

A—Action distance (mainly horizontal)
B—Body motion (mainly vertical)
G—Gain control
P—Placement

These subactivities are arranged in a sequence model consisting of a series of parameters organized in a logical arrangement. The sequence model defines the events or actions that always take place in a preset order when an object is being moved from one location to another. The General Move Sequence model, which is the most commonly used of all available sequence models, is defined as follows:

A	B	G	A	B	P	A
Action distance	Body motion	Grasp	Action distance	Body motion	Placement	Action distance

The subactivities, or sequence model parameters, are then assigned time-related index numbers based on the motion content of the subactivity. This approach provides complete analysis flexibility within the overall scope of the sequence model. For each object moved, any combination of motions could occur, and using MOST, any combination could be analyzed. For the General Move Sequence, these index values are easily memorized from a brief data card, shown in Fig. 17.4.2.

A fully indexed General Move Sequence, for example, might appear as follows:

$$A_6\ B_6\ G_1\ A_1\ B_0\ P_3\ A_0$$

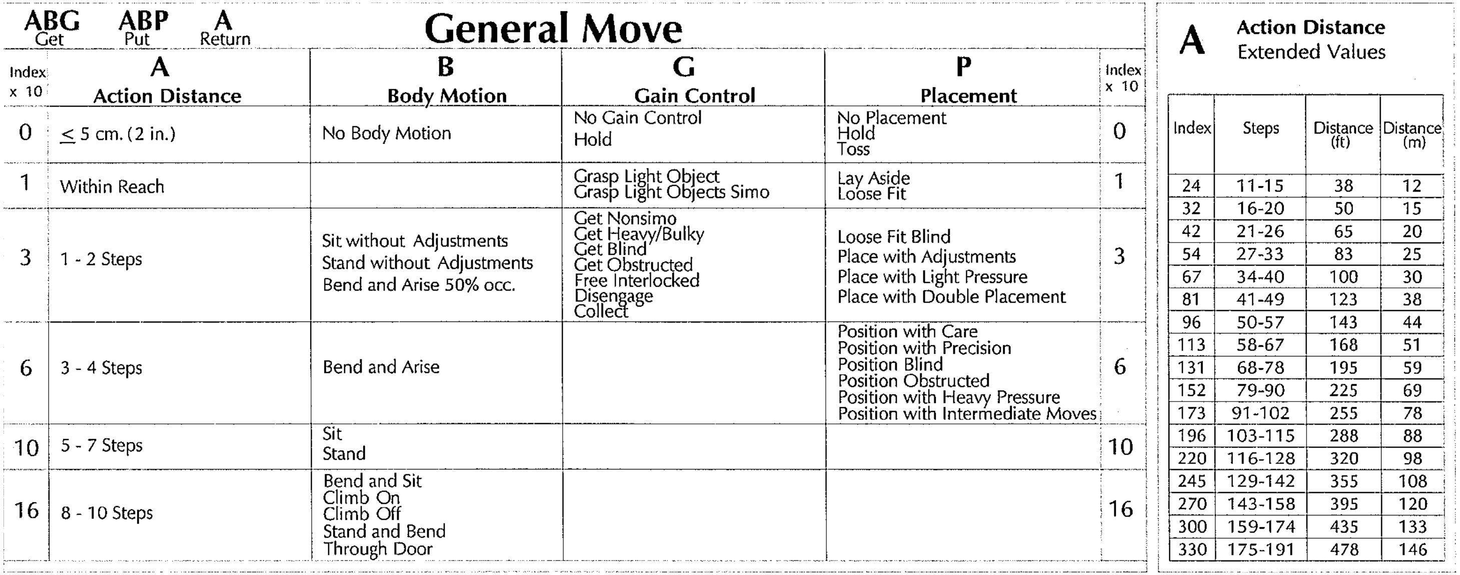
where A_6 = walk three to four steps to object location
B_6 = bend and arise
G_1 = gain control of light object
A_1 = move object a distance within reach
B_0 = no body motion
P_3 = place and adjust object
A_0 = no return

This example could, for instance, represent the following activity: "Walk three steps to pick up a bolt from floor level, arise, and place the bolt in a hole."

General Move is by far the most frequently used of the three sequence models. Roughly 50 percent of all manual work occurs as a General Move, with the percentage running higher for assembly and material-handling work, and lower for machine shop operations.

The second type of move is described by the Controlled Move Sequence. This sequence is used to cover such activities as operating a lever or crank, activating a button or switch, or simply sliding an object over a surface. In addition to the A, B, and G parameters from the General Move Sequence, the sequence model for Controlled Move contains the following subactivities:

M—move Controlled
X—process Time
I—align



ABG Get **ABP** Put **A** Return

General Move

Index x 10	A Action Distance	B Body Motion	G Gain Control	P Placement	Index x 10
0	≤ 5 cm. (2 in.)	No Body Motion	No Gain Control Hold	No Placement Hold Toss	0
1	Within Reach		Grasp Light Object Grasp Light Objects Simo	Lay Aside Loose Fit	1
3	1 - 2 Steps	Sit without Adjustments Stand without Adjustments Bend and Arise 50% occ.	Get Nonsimo Get Heavy/Bulky Get Blind Get Obstructed Free Interlocked Disengage Collect	Loose Fit Blind Place with Adjustments Place with Light Pressure Place with Double Placement	3
6	3 - 4 Steps	Bend and Arise		Position with Care Position with Precision Position Blind Position Obstructed Position with Heavy Pressure Position with Intermediate Moves	6
10	5 - 7 Steps	Sit Stand			10
16	8 - 10 Steps	Bend and Sit Climb On Climb Off Stand and Bend Through Door			16

A **Action Distance**
Extended Values

Index	Steps	Distance (ft)	Distance (m)
24	11-15	38	12
32	16-20	50	15
42	21-26	65	20
54	27-33	83	25
67	34-40	100	30
81	41-49	123	38
96	50-57	143	44
113	58-67	168	51
131	68-78	195	59
152	79-90	225	69
173	91-102	255	78
196	103-115	288	88
220	116-128	320	98
245	129-142	355	108
270	143-158	395	120
300	159-174	435	133
330	175-191	478	146

FIGURE 17.4.2 General Move data card.

As many as one-third of the activities occurring in machine shop operations may involve Controlled Move sequences. A typical activity covered by the Controlled Move Sequence is the engaging of the feed lever on a milling machine. The sequence model for this activity might be indexed as follows:

$$A_1\ B_0\ G_1\ M_1\ X_{10}\ I_0\ A_0$$

where A_1 = reach to the lever a distance within reach
B_0 = no body motion
G_1 = get hold of lever
M_1 = move lever up to 30 cm (12 in) to engage feed
X_{10} = process time of approximately 3.5 seconds
I_0 = no alignment
A_0 = no return

The third sequence model comprising the BasicMOST technique is the Tool Use Sequence model. This sequence model covers the use of hand tools for such activities as fastening or loosening, cutting, cleaning, measuring, and recording. Also, certain activities involving mental processes can be classified as Tool Use, such as reading, inspecting, writing, and marking. The Tool Use Sequence model is a combination of General Move and Controlled Move activities. It was developed as part of the BasicMOST systems, merely to simplify the analysis of activities related to the use of hand tools. It will later become clear that any hand tool activity is made up of General and Controlled Moves.

The use of a wrench, for example, might be described by the following sequence:

$$A_1\ B_0\ G_1\ A_1\ B_0\ P_3\ F_{10}\ A_1\ B_0\ P_1\ A_0$$

where A_1 = reach to wrench a distance within reach
B_0 = no body motion
G_1 = get hold of wrench
A_1 = move wrench to fastener a distance within reach
B_0 = no body motion
P_3 = place wrench on fastener
F_{10} = tighten fastener with wrench
A_1 = move wrench a distance within reach
B_0 = no body motion
P_1 = lay wrench aside
A_0 = no return

Time Units

The time units used in MOST are identical to those used in the basic MTM system and are based on hours and parts of hours called time measurement units (TMUs). One TMU is equivalent to 0.00001 hour.

The time value in TMU for each sequence model is calculated by adding the index numbers and multiplying the sum by 10. In our previous General Move Sequence example, the time would be

$$(6 + 6 + 1 + 1 + 0 + 3 + 0) \times 10 = 170 \text{ TMU}$$

corresponding to approximately 0.01 minute. The time values for the other two examples are computed in the same way. The Controlled Move totals up to

$$(1 + 0 + 1 + 1 + 10 + 0 + 0) \times 10 = 130 \text{ TMU}$$

and the Tool Use

$$(1 + 0 + 1 + 1 + 0 + 3 + 10 + 1 + 0 + 1 + 0) \times 10 = 180 \text{ TMU}$$

All time values established by MOST reflect the pace of an average skilled operator, appropriately instructed and working at a normal performance rate. This is often referred to as the 100 percent performance level that in time study is achieved by using leveling factors to adjust time to defined levels of skill and effort. Therefore, when using MOST, it is not necessary to adjust the time values unless they must conform to particular high or low task plans used by some companies. This also means that if a time standard for an operation is properly established by using either MOST, MTM, or stopwatch time study, the TMU values should be identical or almost identical if the accuracy constraints for the three techniques are met.

The analysis of an operation will consist of a series of sequence models describing the movement of objects to perform the operation. See Fig. 17.4.3 as an example. Total time for the complete MOST analysis is arrived at by adding the computed sequence times. The operation time may be left in TMU or converted to minutes or hours. Again, this time would reflect pure work content (normal time without allowances) at the 100 percent performance level. The final time standard will include the allowance factor PRD: consisting of personal time (P) the rest or fatigue (R or F) factor, and unavoidable delays (D), often determined by a work sampling study. Therefore, if the normal time = 1.0 hour and assuming that the allowance factor (PRD) = 15 percent, then the final time standard = 1.15 hours.

Application Speed

MOST was designed to be considerably faster than other work measurement techniques. Because of its more intuitive structure, under ideal conditions BasicMOST requires only 10 applicator hours per measured hour. (MTM-1 requires 300 to 400 applicator hours per measured hour.)

Accuracy

The accuracy principles that apply to MOST are the same as those used in statistical tolerance control: The accuracy to which a part is manufactured depends on its role in the final assembly. Likewise, with MOST, time values are based on calculations that guarantee the overall accuracy of the final time standard. Based on these principles, MOST provides the means for covering a high volume of manual work with an accuracy that can be determined and controlled.

Method Sensitivity

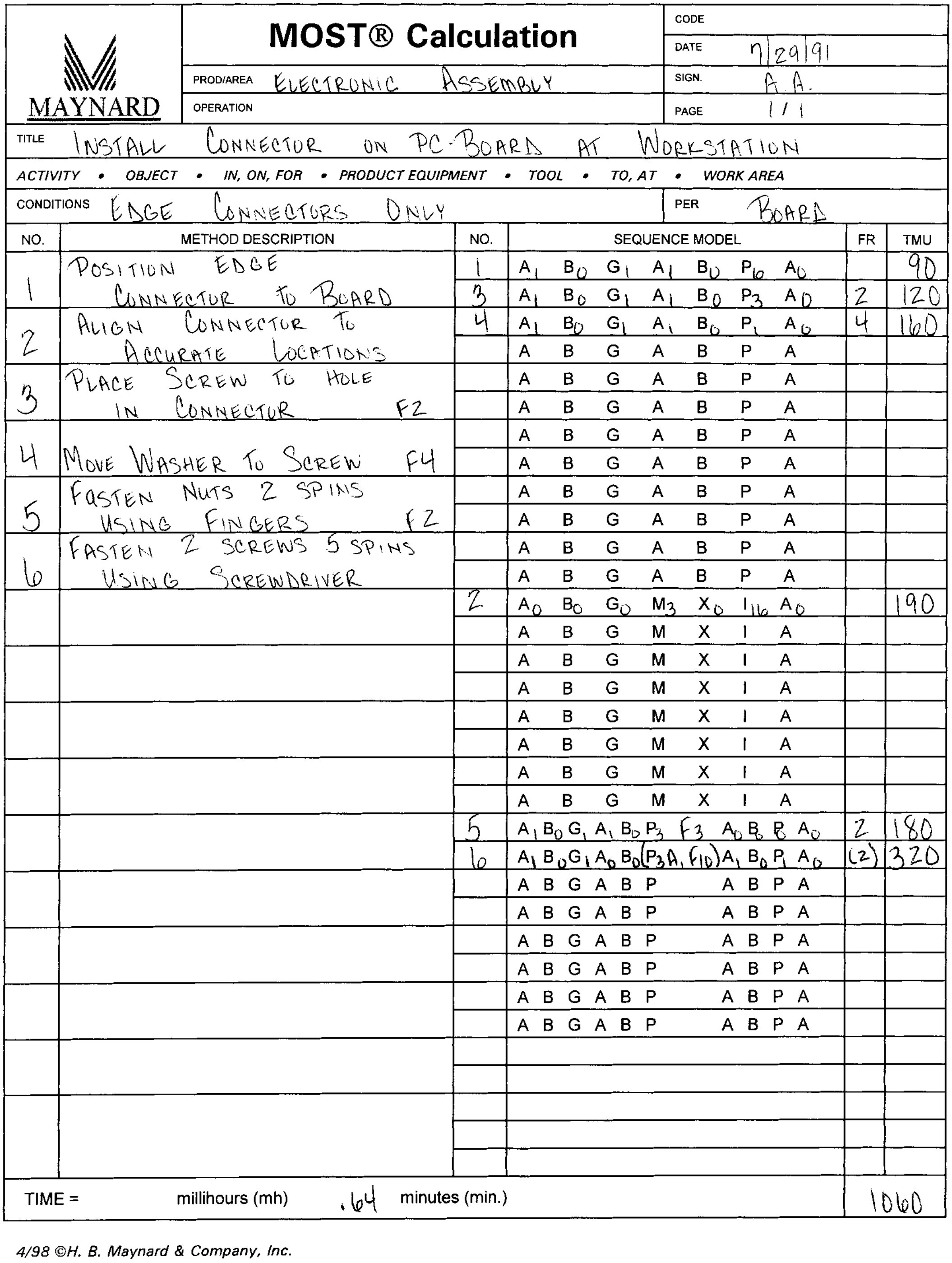
MOST is a method-sensitive technique; that is, it is sensitive to the variations in time generated by different methods. This feature is very effective in evaluating alternative methods of performing operations with regard to time and cost. The MOST analysis will clearly indicate the more economical and less fatiguing method. For instance, the following general move sequence model:

$$A_6\ B_6\ G_3\ A_{10}\ B_0\ P_3\ A_0 \qquad 280\ \text{TMU}$$

symbolizes the movement of a heavy (10 kg) object from a floor pallet to a bench with bend (B_6) and walking (A_6,A_{10}). These high index values indicate that the method is inefficient and ergonomically unacceptable (particularly if repetitive) and therefore an improvement of the workplace is required. By installing an elevated roller conveyor close to the bench, moving the object becomes controlled and more efficient and less fatiguing:

$$A_3\ B_0\ G_3\ M_6\ X_0\ I_0\ A_0 \qquad 120\ \text{TMU}$$

The fact that the MOST system is method sensitive greatly increases its worth as a work measurement tool. Not only does it indicate the time needed to perform various activities, it also



MAYNARD

MOST® Calculation

CODE

DATE 7/29/91

PROD/AREA ELECTRONIC ASSEMBLY

SIGN. A. A.

OPERATION

PAGE 1/1

TITLE INSTALL CONNECTOR ON PC-BOARD AT WORKSTATION

ACTIVITY • OBJECT • IN, ON, FOR • PRODUCT EQUIPMENT • TOOL • TO, AT • WORK AREA

CONDITIONS EDGE CONNECTORS ONLY

PER BOARD

NO.	METHOD DESCRIPTION	NO.	SEQUENCE MODEL	FR	TMU
1	POSITION EDGE CONNECTOR TO BOARD	1	A_1 B_0 G_1 A_1 B_0 P_6 A_0		90
		3	A_1 B_0 G_1 A_1 B_0 P_3 A_0	2	120
2	ALIGN CONNECTOR TO ACCURATE LOCATIONS	4	A_1 B_0 G_1 A_1 B_0 P_1 A_0	4	160
			A B G A B P A		
3	PLACE SCREW TO HOLE IN CONNECTOR F2		A B G A B P A		
			A B G A B P A		
4	MOVE WASHER TO SCREW F4		A B G A B P A		
			A B G A B P A		
5	FASTEN NUTS 2 SPINS USING FINGERS F2		A B G A B P A		
			A B G A B P A		
6	FASTEN 2 SCREWS 5 SPINS USING SCREWDRIVER		A B G A B P A		
			A B G A B P A		
		2	A_0 B_0 G_0 M_3 X_0 I_{16} A_0		190
			A B G M X I A		
			A B G M X I A		
			A B G M X I A		
			A B G M X I A		
			A B G M X I A		
			A B G M X I A		
			A B G M X I A		
		5	A_1 B_0 G_1 A_1 B_0 P_3 F_3 A_0 B_0 P_0 A_0	2	180
		6	A_1 B_0 G_1 A_0 B_0 $(P_3$ A_1 $F_{10})$ A_1 B_0 P_1 A_0	(2)	320
			A B G A B P A B P A		
			A B G A B P A B P A		
			A B G A B P A B P A		
			A B G A B P A B P A		
			A B G A B P A B P A		
			A B G A B P A B P A		

TIME = millihours (mh) .64 minutes (min.) 1060

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FIGURE 17.4.3 Example of MOST analysis.

provides the analyst with an instant clue that a method should be reviewed. The results are clear, concise, easily understood time calculations that indicate the opportunities for saving time, money, and energy.

Documentation

One of the most burdensome problems in the time standards development process is the volume of paperwork required by the most widely used predetermined work measurement systems. Examples have shown that where the more detailed systems require between 40 and 100 pages of documentation, MOST requires as few as 5. For instance, the analysis of a carburetor assembly operation (approximate duration 3 minutes) was done with MTM-1 on 16 pages, MTM-2 on 9 pages, while less than 1 page was needed for the MOST analysis. The substantially reduced amount of paperwork enables analysts to complete studies faster and to update standards more easily. The reduction of paperwork generated by MOST does not lead to a lack of definition of the method used to perform the task. On the contrary, the method generated from a MOST analysis is a clear, concise plain-language description of the activity. These method descriptions can very well be used for operator training and instruction.

Applicability

In what situations can MOST be used? Because manual work normally includes some variation from one cycle to the next, MOST, with its statistically established time ranges and time values, can produce times comparable to more detailed systems for the majority of manual operations. Therefore, MOST is appropriate for any manual work that contains variation from one cycle to another regardless of cycle length. BasicMOST should not be used in situations in which a short cycle (usually up to 10 seconds or 280 TMU) is repeated identically over an extended period of time. In these situations, the more detailed MiniMOST version should be chosen as the proper work measurement tool. In fact, MiniMOST was developed to cover highly repetitive, short-cycled work measurement tasks. At the other end of the spectrum, MaxiMOST was developed to measure long-cycle (2 minutes or more), nonrepetitive operations such as heavy assembly, maintenance, and machine setups.

THE GENERAL MOVE SEQUENCE MODEL

The General Move Sequence deals with the spatial displacement of one or more object(s). Under manual control, the object follows an unrestricted path through the air. If the object is in contact with or restrained in any way by another object during the move, the General Move Sequence should not be used.

Characteristically, General Move follows a fixed sequence of subactivities identified by the following steps:

1. Reach with one or two hands a distance to the object(s), either directly or in conjunction with body motions.
2. Gain manual control of the object(s).
3. Move the object(s) a distance to the point of placement, either directly or in conjunction with body motions.
4. Place the object(s) in a temporary or final position.
5. Return to workplace.

These five subactivities form the basis for the activity sequence describing the manual displacement of the object(s) freely through space. This sequence describes the manual events that can occur when moving an object freely through the air and is therefore known as a *sequence model.* The major function of the sequence model is to guide the attention of the analyst through an operation, thereby adding the dimension of having a preprinted and standardized analysis format. The existence of the sequence model provides for increased analyst consistency and reduced subactivity omissions.

The Sequence Model

The sequence model takes the form of a series of letters representing each of the various subactivities (called parameters) of the General Move Activity Sequence model. With the exception of an additional parameter for body motions, the General Move Sequence is the same as the preceding five-step pattern:

A B G A B P A

where A = Action distance
B = Body motion
G = Gain control
P = Placement

The parameters can be grouped into three phases, Get, Put, and Return:

ABG	ABP	A
Get	Put	Return

Parameter Definitions

A Action Distance. This parameter covers all spatial movement or actions of the fingers, hands, and/or feet, either loaded or unloaded. Any control of these actions by the surroundings requires the use of other parameters.

B Body Motion. This parameter refers to either vertical (up and down) motions of the body or the actions necessary to overcome an obstruction or impairment to body movement.

G Gain Control. This parameter covers all manual motions (mainly finger, hand, and foot) employed to obtain complete manual control of an object(s) and to subsequently relinquish that control. The G parameter can include one or several short-move motions whose objective is to gain full control of the object(s) before it is to be moved to another location.

P Placement. This parameter refers to actions at the final stage of an object's displacement to align, orient, and/or engage the object with another object(s) before control of the object is relinquished.

Parameter Indexing

Index values for these four parameters included in the General Move Sequence model can be found in Fig. 17.4.2. Definitions of all available index values for the four General Move parameters can be found in *MOST Work Measurement Systems* [1]. The definitions for Action distance (A) have been included below as an example.

Action Distance (A). Action distance covers all spatial movement or actions of the fingers, hands, and/or feet, either loaded or unloaded. Any control of these actions by the surroundings requires the use of other parameters.

A_0 < 5 cm (2 in). Any displacement of the fingers, hands, and/or feet a distance less than or equal to 5 cm (2 in) will carry a zero index value. The time for performing these short distances is included within the Gain control and Place parameters. Example: Reaching between the number keys on a pocket calculator or placing nuts or washers on bolts located less than 5 cm (2 in) apart.

A_1 Within Reach. Actions are confined to an area described by the arc of the outstretched arm pivoted about the shoulder. With body assistance—a short bending or turning of the body from the waist—this within reach area is extended somewhat. However, taking a step for further extension of the area exceeds the limits of an A_1 and must be analyzed with an A_3 (one to two steps).

Example: With the operator seated in front of a well-laid-out workbench, all parts and tools can be reached without displacing the body by taking a step.

The parameter value A_1 also applies to the actions of the leg or foot reaching to an object, lever, or pedal. If the trunk of the body is shifted, however, the action must be considered a step (A_3).

A_3 One to Two Steps. The trunk of the body is shifted or displaced by walking, stepping to the side, or turning the body around using one or two steps. Steps refers to the total number of times each foot hits the floor.

Index values for longer-action distances involving walking on flat surfaces, as well as up or down normally inclined stair steps can be found in Fig. 17.4.2 for up to 10 steps. This will satisfy the need for action distance values for most work areas in a manufacturing plant. Should, however, longer walking distance occur, a table of extended values is available. All index values for walking are based on an average step length of 0.75 m (2½ ft).

General Move Examples

1. A man walks four steps to a small suitcase, picks it up from the floor, and without moving, further places it on a table located within reach.

$$A_6\ B_6\ G_1\ A_1\ B_0\ P_1\ A_0 \qquad 150\ \text{TMU}$$

2. An operator standing in front of a lathe walks six steps to a heavy part lying on the floor, picks up the part, walks six steps back to the machine, and places it in a 3-jaw chuck with several adjusting actions. The part must be inserted 5 cm (2 in) into the chuck jaws.

$$A_{10}\ B_6\ G_3\ A_{10}\ B_0\ P_3\ A_0 \qquad 320\ \text{TMU}$$

3. From a stack located 3 m (10 ft) away, a heavy object must be picked up and moved 2 m (5 ft) and placed on top of a workbench with some adjustments. The height of this stack will vary from waist to floor level. Following the placement of the object on the workbench, the operator returns to the original location, which is 3.5 m (11 ft) away.

$$A_6\ B_3\ G_3\ A_3\ B_0\ P_3\ A_{10} \qquad 280\ \text{TMU}$$

THE CONTROLLED MOVE SEQUENCE MODEL

The Controlled Move Sequence describes the manual displacement of an object over a controlled path. Movement of the object is restricted in at least one direction by contact with or an attachment to another object or the nature of the work demands that the object be deliberately moved along a specific or controlled path.

The Sequence Model

The sequence model takes the form of a series of letters representing each of the various subactivities (called parameters) of the Controlled Move Activity Sequence.

A B G M X I A

where A = Action distance
B = Body motion
G = Gain control
M = Move controlled
X = Process time
I = Align

with the phases

A B G	M X I	A
Get	Move or actuate	Return

Parameter Definitions

Only three new parameters are introduced, because the A, B, and G parameters were discussed with the General Move Sequence and remain unchanged.

M Move Controlled. This parameter covers all manually guided movements or actions of an object over a controlled path.

X Process Time. This parameter occurs as that portion of work controlled by processes or machines and not by manual actions.

I Align. This parameter refers to manual actions following the controlled move or at the conclusion of process time to achieve the alignment of objects.

The index value definitions for these parameters (M, X, and I) can be found in the textbook *MOST Work Measurement Systems* [1].

Controlled Move Examples

1. From a position in front of a lathe, the operator takes two steps to the side, turns the crank two revolutions, and sets the machining tool against a scale mark.

$A_3\ B_0\ G_1\ M_6\ X_0\ I_6\ A_0$ 160 TMU

2. A milling cutter operator walks four steps to the quick-feeding cross lever and engages the feed. The machine time following the 10 cm (4 in) lever action is 2.5 seconds.

$A_6\ B_0\ G_1\ M_1\ X_6\ I_0\ A_0$ 140 TMU

3. A material handler takes hold of a heavy carton with both hands and pushes it 45 cm (18 in) across conveyor rollers.

$$A_1\ B_0\ G_3\ M_3\ X_0\ I_0\ A_0 \qquad 70\ \text{TMU}$$

4. Using the foot pedal to activate the machine, a sewing machine operator makes a stitch requiring 3.5 seconds process time. (The operator must reach the pedal with the foot.)

$$A_1\ B_0\ G_1\ M_1\ X_{10}\ I_0\ A_0 \qquad 130\ \text{TMU}$$

THE TOOL USE SEQUENCE MODEL

The Tool Use Sequence is composed of subactivities from the General Move Sequence, along with specially designed parameters describing the actions performed with hand tools, power tools, or in some cases, the use of certain mental processes. Tool Use follows a fixed sequence of subactivities occurring in five main activity phases:

1. Get object or tool
2. Place object or tool in working position
3. Use tool
4. Put aside object or tool
5. Return to workplace

The Sequence Model

These five activity phases form the basis for the activity sequence describing the handling and use of hand tools. The sequence model takes the form of a series of letters representing each of the various subactivities of the Tool Use Activity Sequence:

ABG	ABP		ABP	A
Get object or tool	Place object or tool	Use tool	Aside object or tool	Return

where *A* = Action distance
B = Body motion
G = Gain control
P = Place

The space in the sequence model for Use tool is provided for the insertion of one of the following Tool Use parameters. These parameters referring to the specifications of using the tool are

F—Fasten
L—Loosen
C—Cut
S—Surface treat
M—Measure
R—Record
T—Think

Tool Use Examples for Fasten and Loosen

1. Obtain a nut from a parts bin located within reach, place it on a bolt, and run it down with seven finger actions.

$$A_1\ B_0\ G_1\ A_1\ B_0\ P_3\ F_{10}\ A_0\ B_0\ P_0\ A_0 \qquad 160\ \text{TMU}$$

2. Obtain a power wrench from within reach, run down four 10 mm (⅜ in) bolts located 15 cm (6 ins) apart, and set aside wrench.

$$A_1\ B_0\ G_1\ A_0\ B_0\ (P_3\ A_1\ F_6)\ A_1\ B_0\ P_1\ A_0\ (4) \qquad 440\ \text{TMU}$$

3. From a position in front of an engine lathe, obtain a large T-wrench located five steps away and loosen one bolt on a chuck on the engine lathe with both hands using five arm actions. Set aside the T-wrench from the machine (within reach).

$$A_{10}\ B_0\ G_1\ A_{10}\ B_0\ P_3\ L_{24}\ A_1\ B_0\ P_1\ A_0 \qquad 500\ \text{TMU}$$

THE MOST SYSTEMS FAMILY

In addition to the BasicMOST systems, several specific application-oriented versions of MOST are now members of the MOST systems family: MiniMOST, MaxiMOST, and ClericalMOST.

The MiniMOST System

Although the original BasicMOST version can be applied to nonidentical operations of 10 seconds or less and still meet the accuracy criteria, BasicMOST was not designed to measure repetitive short-cycled operations.

Therefore, the MiniMOST version of MOST work measurement systems was developed to satisfy the accuracy requirements that apply to very short-cycled, highly repetitive, identical operations. Such operations may vary from 2 to 10 seconds in time and often are being performed over long periods of time.

MiniMOST consists of two sequence models:

General Move	A B G A B P A
Controlled Move	A B G M X I A

These sequence models are identical to the two fundamental sequence models in the BasicMOST version. There is one major difference, however. The multiplier for the index value total is 1 for MiniMOST. Therefore, if the sum of the applied index values is 64, this is also the total TMU value for the sequence model. Another difference compared with BasicMOST is that distances in MiniMOST will be measured in centimeters (inches). The application speed of MiniMOST is about 25:1 under ideal conditions compared with about 10:1 for BasicMOST.

The definitions and descriptions of the parameters and elements in MiniMOST have been excluded because of space considerations. The second edition of *MOST Work Measurement Systems* [1] includes a complete description of the MiniMOST work measurement system.

The MaxiMOST System

To satisfy the need for a fast, less detailed but still accurate and consistent system for the measurement of long-cycled, nonrepetitive, nonidentical operations, MaxiMOST was developed.

MaxiMOST consists of five sequence models with a multiplier of 100:

Part Handling	A B P
Tool/Equipment Use	A B T
Machine Handling	A B M
Transport with Powered Crane	A T K T P T A
Transport with Wheeled Truck	A S T L T L T A

MaxiMOST has an application speed of between 3 and 5 to 1 (analyst to measured hours) and is therefore a very cost-effective technique to use in a large number of cases where minute details are unnecessary or even detrimental to proper work instructions. The recommendation is to use MaxiMOST for nonidentical cycles that are 2 minutes or longer.

The definitions and descriptions of the parameters and elements in the MaxiMOST system have been excluded because of space considerations. The second edition of *MOST Work Measurement Systems* [1] includes a complete description of the MaxiMOST work measurement system.

ClericalMOST

ClericalMOST is based on three sequence models identical to those in BasicMOST:

General Move
Controlled Move
Tool/Equipment Use (two data cards)

PRINCIPLES AND PROCEDURES FOR DEVELOPING TIME STANDARDS BASED ON MOST SYSTEMS

Calculation Form

A standard MOST calculation form should be used for all analysis work using BasicMOST. (Similar forms have been designed for use with MiniMOST and MaxiMOST.) As illustrated in Fig. 17.4.3, this form consists of four sections:

1. A header identifying the activity to be measured and the work center (area) in which it is being performed
2. A step-by-step method description (left half of form)
3. Preprinted sequence models in three groups—General Move, Controlled Move, and Tool Use
4. A field for the time value or time standard for the activity (bottom part)

Note. The activity or normal time does not include any allowances at this stage. Prior to applying a time standard, appropriate allowances should be added to the normal time on the form, thereby constituting the standard time for the operation.

A frequency factor (Fr) for each sequence model can be specified in the column next to the TMU value column for the sequence model. Normally, the space provided on one page of the MOST calculation form will allow for analyses up to approximately 1 minute.

In all situations where MOST is being used, the top-down approach should be followed. A two-step decision model can be put to use with the first generation being: Is it appropriate and practical to do direct measurement? If "yes," the work should be measured by using the MOST calculation form. If the answer is "no," the operations or activities for the plant, department, or work center should be broken down into logical suboperations. Using the top-down technique, each suboperation should then be measured using MOST and placed on a work sheet for the calculation of time standards. In some instances (e.g., for long-cycle operations), suboperations may have to be broken down still one more level and thereafter be merged into combined suboperations before assigning them onto the work sheet. (See Chap. 5.4 regarding the calculation of labor standards.)

By following the top-down approach, the database with standard data (suboperation data) will remain compact and more manageable than if the conventional bottom-up procedure is applied. In most cases, only 200 to 500 suboperations will be required to calculate any number of required time standards.

MOST is an application-oriented or user-friendly system that will require some un-learning and re-thinking by its users experienced in conventional work measurement. It is a new concept not only regarding work measurement but also in the application areas.

MOST for Windows®

The logical sequence model approach lends itself very well to a computerized application. Therefore, in 1976, the first lines of code were written in an effort to develop a software program that would advance the state-of-the-art work measurement. While other computerized systems use element symbols or numerical data as input, MOST for Windows initially used method descriptions expressed in plain English, like a language-based expert system. Since then MOST for Windows has been updated with improved capabilities and increased user friendliness as a result. (See Chap. 5.6 Computerized Labor Standards for further information on MOST for Windows.)

AutoMOST

The purpose of using MOST is to establish accurate and consistent time standards. Several methods to accomplish this are available, most often based on a process of selecting MOST standard data elements from a work sheet. By using expert system technology, the selection process can be automated. AutoMOST is a knowledge-based development tool that will automatically create time standards from electronic or manual input of product data. (See Chaps. 5.6 and 5.9 for additional information about AutoMOST.)

SUMMARY AND FUTURE TRENDS

During the 1950s and 1960s, the work measurement field became inflated with conventional derivatives of the original MTM system (MTM-1) first published in 1948. That trend has continued to some extent with one exception: MOST. In the mid-1960s, a new approach, a more practical and user-friendly method (and perhaps more important, a faster, simpler, and more cost-effective technique) was necessary to maintain a high level of interest in work measurement. MOST seems to have been the answer. Over 30,000 people representing more than 4000 organizations have become certified MOST users. MOST has been translated into at least 15 languages and is in use in more than 35 countries around the world. MOST satisfies all the criteria of simplicity, speed, accuracy, consistency, applicability, integrity, and universality that can be expected from a modern work measurement technique and system. MOST for Windows represents the state of the art in the area of computerized work measurement, and users enthusiastically endorse and support MOST.

MOST WORK MEASUREMENT SYSTEMS

Traditionally, the manufacturing industry has been and still is the most active user of work measurement. The main reason for this is the long-term emphasis on productivity improvements and performance-based systems. Billions of dollars have been saved as a result of proper and focused application of work measurement. However, the service industry and other industries are becoming more and more interested in applying and gaining the benefits of work measurement. For instance, service industries are now applying work standards for staffing, planning, budgeting, and so on. (See for instance Chaps. 10.7, 15.4, and 15.6.)

A renaissance in work measurement became noticeable during the 1980s in the defense industry because of a military standard (MIL-STD-1567A) issued by the U.S. Department of Defense in 1983. At first, defense contractors were obligated to comply with this standard on major contracts. Compliance includes fully documented time standards (80 percent coverage) based on a recognized predetermined motion time system. MOST is successfully being used by major defense contractors to satisfy the requirements of MIL-STD-1567A. During the 1990s the standard was not enforced as planned.

Despite the efforts by industry to increasingly mechanize manufacturing operations, the measurement of work done by people is here to stay for many more years. The advantages of knowing and being able to plan from realistic and consistent standards are just too great to dismiss. A good example is the well-known New United Motor Manufacturing Co. (NUMMI) project, a successful joint venture between General Motors and Toyota. A great deal of the success has been attributed to the back-to-basics standardization that was a cornerstone in the project and is well documented in the article “Time and Motion Regained” by Paul S. Adler [2].

During the past 10 years, the work measurement and standard setting procedures have become simpler, faster, and more integrated with other functions to attract the attention they deserve. Manual MOST and MOST for Windows have proven to meet those criteria. But, more can be done and more will be done. Today’s computer technology has reached a level that cannot be ignored by work measurement specialists. By taking advantage of this technology, time standards could and should become a logical and integral part of any business system as is the case in many companies already.

The general trend in industry is automation. Therefore, it is obvious that we will see fully automated procedures (i.e., AutoMOST) for calculating and updating time standards based on data developed and maintained by industrial engineers. A direct link to a computer-aided design (CAD) or business resource planning (BRP) system with the purpose of producing process plans, schedules, and cost estimates based on accurate and consistent time standards will likely become a common practice within the next few years. Standards to cover the activities for activity-based costing (ABC) systems will also be needed. Finally, it will be necessary to simplify the application of presently used work measurement systems including MOST to such a degree that all staff in a company can learn how to use them and benefit from them in their ongoing effort to make continuous improvements. To achieve these goals it will be necessary to stimulate the employees both in industry and services, and students in universities and colleges to adopt a positive attitude toward a fundamental and widely used industrial engineering discipline: the *measurement of work.*

Work measurement: the science that brings more and better knowledge to people about work and how to improve work.

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BIOGRAPHY

Kjell B. Zandin, is a senior vice president at H. B. Maynard and Company, Inc., Pittsburgh, Pennsylvania. In the late 1960s, he developed a new concept of work measurement that subsequently became the Maynard Operation Sequence Technique (MOST®) systems. Zandin authored the book *MOST® Work Measurement Systems* published by Marcel Dekker, New York, in 1980 (first edition) and 1990 (second edition). In 1986, Zandin was the recipient of the first Technical Innovation in Industrial Engineering Award presented by the Institute of Industrial Engineers for his significant innovative contributions to the industrial engineering profession. In 1990, he received the Royal Charter Award from the Institution of Production Engineers in Great Britain. Zandin has served on the Visiting Committee for the Industrial Engineering Department at the University of Pittsburgh since 1987 and on the board of directors of the Pittsburgh Chapter of the Institute of Industrial Engineers since 1997. He is a senior member of the Institute of Industrial Engineers and a Fellow of the World Academy of Productivity Science. Zandin holds an M.Sc. degree from Chalmers University of Technology in Gothenburg, Sweden.

Source: MAYNARD'S INDUSTRIAL ENGINEERING HANDBOOK

CHAPTER 17.5

LEARNING CURVES

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Learning curves have been used for over 50 years since T. P. Wright observed the cumulative unit cost to produce an airplane decreased at a predictable rate as the quantity produced increased. Industrial engineers have used learning curves to estimate the higher cost of initial production at different points in time and for different production volumes until the factory workers are able to achieve the industrial engineered *standard time* established. This chapter defines and explains the underlying factors affecting not being able to achieve standard time and the learning curves used to predict variance from standard, or *realization factor,* as it is sometimes referred to. Operator learning is only one of the key elements that affect achieving standard time. There is product and process learning and loss of learning due to breaks in production in addition to logistics and technical elements. There is considerable variability in estimating the realization factor applied to standard times. This detailed analysis of the many factors or elements that define why standard time is not met were the foundation of the aerospace and defense industry position in the U.S. Senate hearings on work measurement in 1985. Furthermore, current and future issues impacting learning are discussed, such as the effect of automation, self-empowered workforce, and future trends in product and process innovation. Discussions of both the unit cost and cumulative average cost approaches to learning curves, as well as the basic algebraic logarithm equation, are also discussed.

BACKGROUND

Frederick Taylor Model of Manufacturing

The Frederick Taylor model of manufacturing, as it has commonly been applied for almost a century, moved technological knowledge about the process away from factory workers to industrial engineers. The workplace layout and methods employed for a given manufacturing process are prescribed by these staff engineers. Thus, factory workers have been encouraged to leave their brains at home and only follow orders. If workers do not understand the process, they cannot handle unanticipated situations, nor can they do much to improve the process, even if they are motivated. Typically, in the past, a manufacturing process has not been scientifically developed from a product and process variability standpoint, and therefore process variability will occur. Companies have used time-and-motion studies to find the "one best way" to produce an item, but they rarely have found the root cause of product and/or process variability. Since workers for the most part have been deskilled, they are not capable of solving the problem quickly, thus accentuating the problem.

Thus, a lot more manufacturing process changes will be made based on the workers' knowledge, not that of the industrial engineer. The industrial engineer, instead, will apply his or her overall manufacturing process generalist knowledge to assist the design engineer design for manufacturability and producibility, thus greatly reducing process variability, which has impacted the learning curve in the past.

What Is a Learning Curve?

The book, *Industrial Engineering Terminology* [1], defines *learning curve* as "a plot of productive output or unit work times of an individual or group as a function of time or output per unit time; used to predict the learning rate in starting up a new job or project. A learning curve is usually exponential and flattens out with time." A *startup curve* is defined as "a learning curve applied to a job or process to adjust for work times longer than standard, or average, as a result of the introduction of a new job or new worker(s)." The aerospace and defense industry [2] defines *realization factor* as "the ratio of estimated actual time to perform a task divided by the IE established standard time earned either for a particular or cumulative number of units produced." In the aerospace and defense industry, the terms *learning curve, improvement curve,* and *realization factor* are sometimes used interchangeably. However, *learning curve* usually refers only to improvement due to operator learning, while the *improvement curve* is the result of cumulative gains in effectivity made by the organization, much of which is not impacted by the operator. Figure 17.5.1 highlights the key elements of a typical improvement curve, which are standard time, methods improvement, learning, logistics, technical, and miscellaneous. These key elements are discussed in

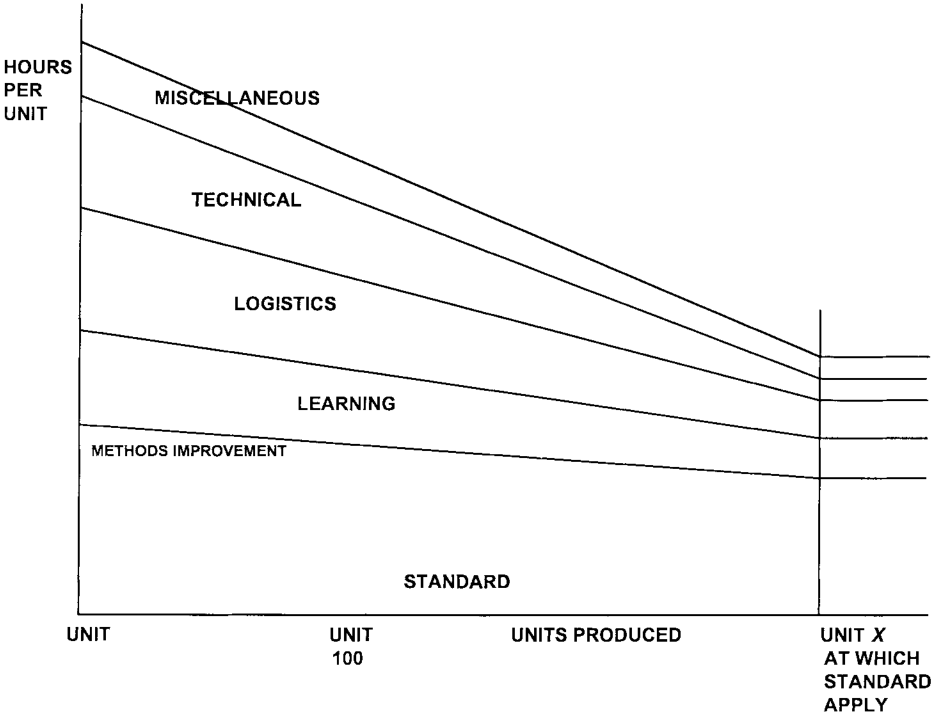

FIGURE 17.5.1 Typical improvement curve.

detail in the section entitled "Learning (Improvement) Curve Elements." In the commercial world, the term *startup curve* is more commonly used, of which learning is only one of the factors influencing startup costs.

What Is Standard Time?

Industrial Engineering Terminology [1] defines *standard time* as "a unit time value of a work task as determined by the proper application of appropriate work measurement techniques by qualified personnel. Generally established by applying appropriate allowances to normal time." *Normal time* is defined as "the time required by a qualified operator to perform a task at a normal pace to complete an element, cycle, or operation using a prescribed method" [1]. *Allowance* is defined as "a time value or percentage of time by which the normal time is increased, for the amount of non-productive time applied, to compensate for justifiable causes or policy requirements which necessitate performance time not directly measured for each element or task. Usually includes: irregular elements, incentive opportunity on machine control time, minor unavoidable delays, rest time to overcome fatigue, and times for personal needs" [1].

The aerospace and defense industry [2] defined *standard time* in laymen's terms as "the time required for a fully trained operator to complete a defined element of work to known specifications following a prescribed method utilizing specific equipment, tools, material and work place layout, including average personal, fatigue and delayed time allowance. Standard time is theoretically achievable when rework and scrap are eliminated, all production rate tooling is available, engineering requirements and manufacturing processes have stabilized, machine down time is eliminated, labor is perfectly matched to schedule requirement, parts/material shortage problems have been eliminated, workers become familiar with all aspects of the job and work has been repeated in a stable environment many times, e.g., hundred to thousands. All of these conditions are seldom, if ever, achieved except on high volume, short cycle, mature and stable product operations" [2].

Learning Curve Equation

The most common and useful learning curve model was developed in 1925 by Colonel L. McDill at McCook Field (Wright Patterson Air Force Base, Dayton, Ohio). T. P. Wright of Curtis Wright Corporation in Buffalo, New York, first applied what is now commonly called the *Wright curve.* He observed the cumulative unit cost to produce an airplane decreased at a predictable rate as the quantity produced increased. Wright noticed a predictable cost reduction rate in which the cumulative unit cost decreased by a constant percentage as the cumulative quantity increased by another constant percentage. The cumulative average curve (see Fig. 17.5.2) identifies the cumulative average cost for the *n*th unit and quantity in production, plotted cumulatively. Wright's original model has remained most popular mainly because of the simplicity of its application.

The other most common application is the *unit cost curve* (Crawford theory). The unit cost curve (see Fig. 17.5.3) identifies the unit cost for that particular *n*th unit of production, again plotted cumulatively.

In both instances, the *improvement curve theory,* simply stated, is that as the cumulative production quantity doubles, a specific cost improvement will occur. A 90 percent improvement curve assumes that as the cumulative production quantity doubles, the cost [either unit (Crawford) or cumulative average (Wright) cost] will be 90 percent of the former cost, which is a 10 percent cost reduction. Similarly, for an 80 percent improvement curve, a 20 percent cost reduction will occur as the cumulative production quantity is doubled.

The expression of the Wright model is an algebraic power function and has a mathematical form:

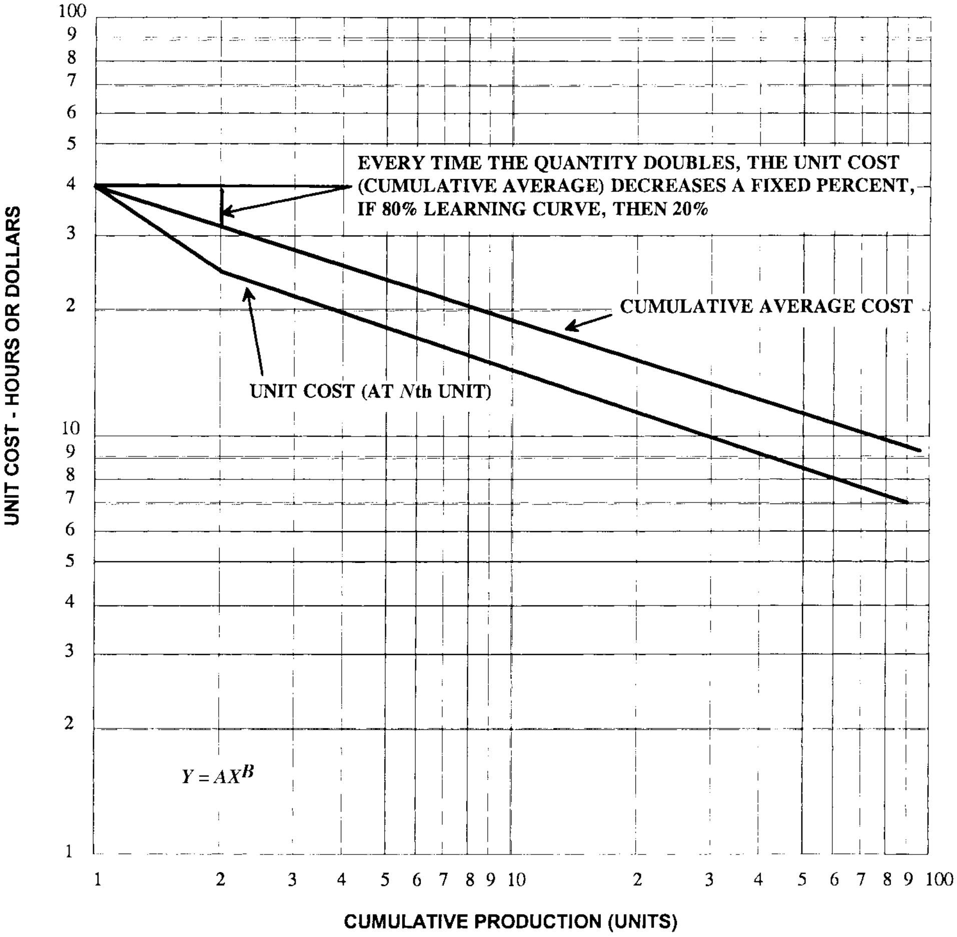

FIGURE 17.5.2 Cumulative average learning curve (Wright Theory).

$$\text{Cumulative average time per unit } (C) = FX^{-n}$$

where F is the cost of the first unit produced, X is the cumulative quantity of units produced, and n is the learning rate. The value of n is usually related to learning curve percent by the equation: n = log learning curve rate (0.8 equals 80 percent learning curve expressed as a decimal) divided by log 2. Table 17.5.1 is an example of this time-versus-quantity relationship for an 80 percent learning curve. Figure 17.5.4 is a simple graph of the data presented in Table 17.5.1.

When the equation for either of the two curves ($c = FX^{-n}$) is plotted on regular (arithmetic) graph paper, a curve is obtained. However, if log-log graph paper is used to plot the equation, a straight line will result with descending slope as the cumulative production increases on the x-axis. The unit cost, in hours or dollars, is plotted on the y-axis. When the factors based on the Wright (cumulative average) theory are being used in developing the improvement curve, the cumulative average is linear, and unit cost is nonlinear for the first units. The inverse is true for the Crawford (unit) theory: the unit cost is linear, and the cumulative average cost is nonlinear for the first units.

LEARNING CURVES

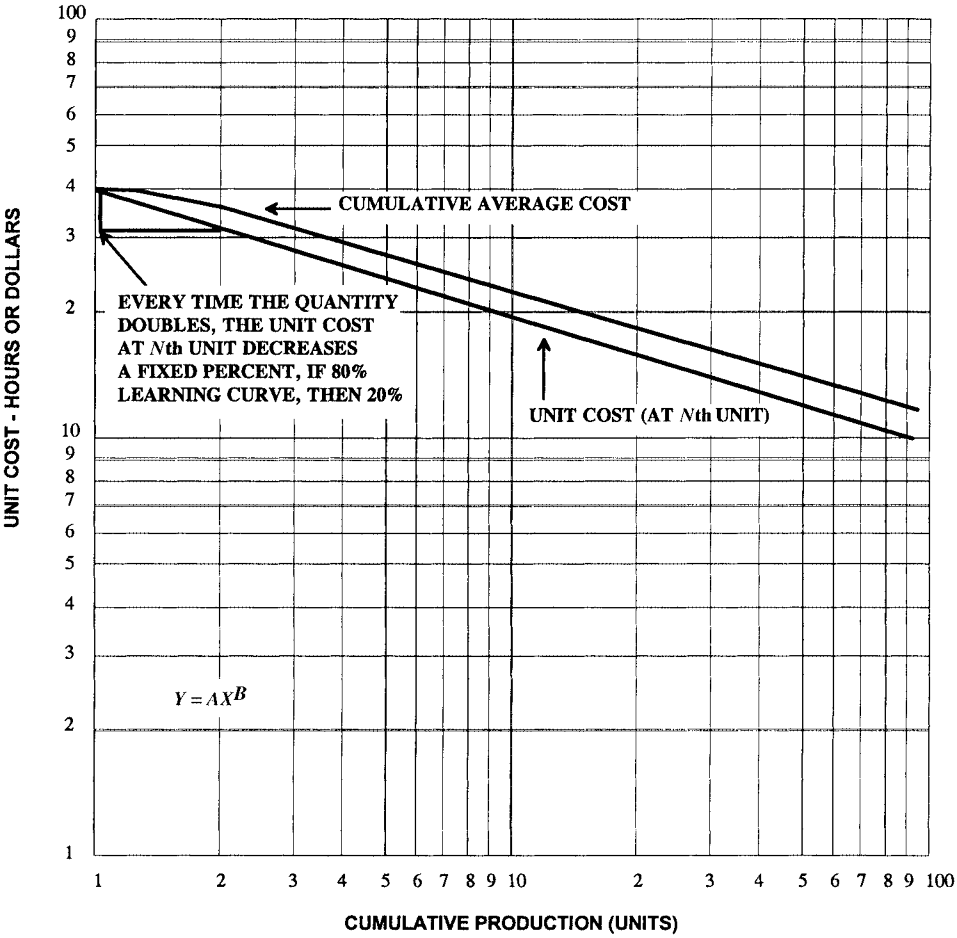

FIGURE 17.5.3 Unit cost learning curve (Crawford Theory).

In either theory, Crawford or Wright, the cumulative average and unit costs are the same for the first unit. However, for subsequent production the cumulative average is always greater than the unit cost for the *n*th cumulative unit of production. Nevertheless, as the production quantity increases at the *n*th unit, the difference between the cumulative average and unit costs stabilizes.

Uses of Learning Curve and Realization Factor

The learning curve has been and will continue to be an effective methodology and tool in which management can determine (1) the future cost of manufacturing a product; (2) the future workforce, equipment, and plant capacity impact; and (3) cost pricing negotiation strategy, especially in the aerospace and defense industry. This chapter on learning curves is focused on discussing all of the elements that need to be considered in assessing *learning* in the broadest context. Learning curves in the past have primarily focused on operator learn-

TABLE 17.5.1 Example of Cost Quantity Relationship for an 80 Percent Learning Curve

Cumulative quantity produced	Cumulative average hours per unit	Learning curve rate
1	40.0	1
2	32.0	80%
4	25.6	80%
8	20.48	80%
16	16.384	80%
32	13.1072	80%
64	10.48576	80%

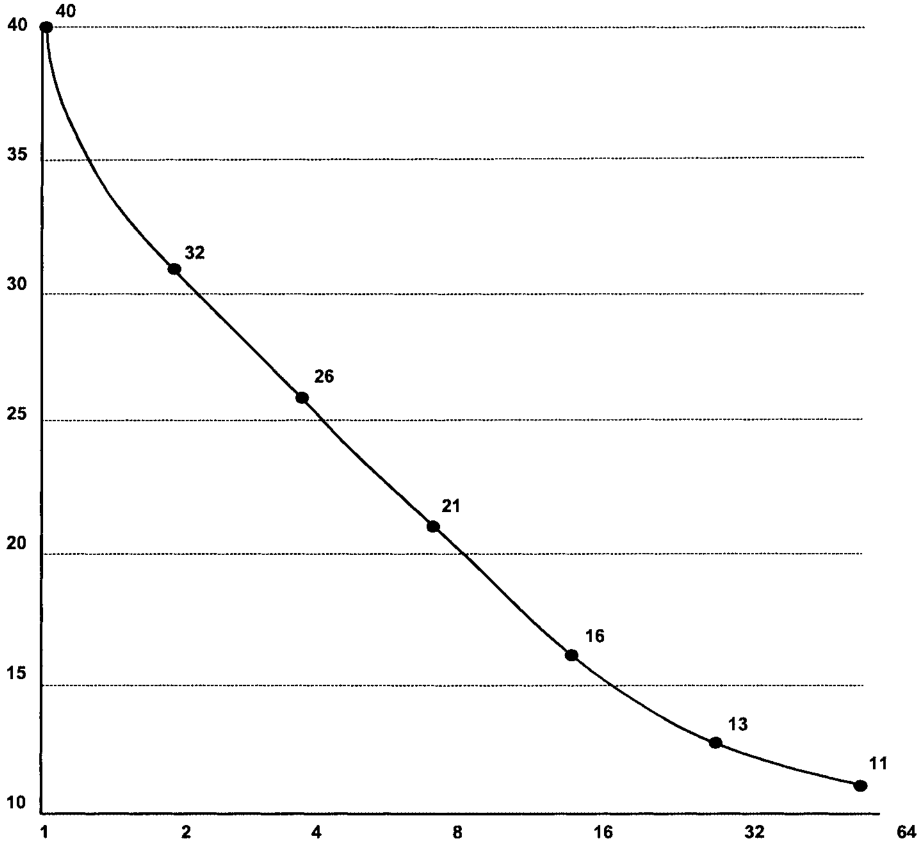

FIGURE 17.5.4 Graph of data in Table 5.1.

ing; however, as factory labor becomes a less significant manufacturing cost driver, the other factors that influence improvement must be considered.

LEARNING (IMPROVEMENT) CURVE ELEMENTS

As presented in the Senate hearings on work measurements in 1985 [2], actual time variance from standard time can be categorized as learning, logistics, technical, and miscellaneous variance. It should be noted, as shown in Figs. 17.5.1 and 17.5.5, that these variance-from-the-standard categories all approach standard over time. Each of these variance-from-the-standard categories composes the real improvement opportunity, requiring specific management action to eliminate the time and cost drivers, not just operator learning.

Learning. There are three key elements affecting learning: (1) operator methods proficiency, (2) product and process familiarity, and (3) loss of learning.

Operator Methods Proficiency. Commercially accepted predetermined time standard data accuracy and reliability criteria are based on a two-minute average cycle time, which is mostly applicable to high-volume commercial industry. The complexity of the operation, the length of job cycle time, the redundancy of identical patterns of motions done repeatedly in the course of performing the operation, and the process capability to meet design requirements all influence the ability or inability of an operator to achieve the normal standard methods level of learning proficiency.

There are four levels of operator method proficiency recognized in the original development of Methods Time Measurement (MTM)-predetermined time standard data [3–5], as shown in Fig. 17.5.6. Several current MTM-based systems, as well as other method-predetermined systems, account for the various levels in standard time development. The normal standard methods level, or 100 percent, is based on performing simultaneous manipulations during the reach move. The low methods level is 169 percent of normal standard time based on sequential (single hand) moves, no manipulation action during the reach move. The high methods level is 138 percent of normal standard time that requires simultaneous two-hand moves, no manipulation actions during the reach move. The optimum methods level is 94 percent of normal standard time, based on higher-class actions using the eye, brain, and/or ear to be accomplished during the reach move.

It is unreasonable to think that an operator can achieve normal standard methods level without repetitive production experience. In the aerospace and defense industry, standard time is quoted as being achievable at the 1000th unit (Wright theory) [2]. In commercial industry application, with an average two-minute cycle time, 1000 units represent 33.3 hours, or one week, of elapsed time. Conversely, for the aerospace and defense industry, average assembly cycle time (90 minutes standard time), 1500 hours, or a minimum of nine months, is required of repetitive production to achieve the status of a fully trained worker.

Product and Process Familiarity. Two of the key elements influencing the level of operation methods proficiency are familiarity with the product and process. Standard time can be best achieved when an operator is performing the same operation (process) each day or the same parts or assemblies (product). Each process and product can have unique technical performance requirements necessitating a different method to be performed. Product familiarity is that number of repetitive cycles to become fully trained in the idiosyncrasies of specific product requirements different from other similar products performed by the same operator. This is particularly true of aerospace and defense industry products with their myriad military specifications, many times unique to a specific product division of a specific service. Process familiarity is that number of repetition cycles to become fully trained in the basic skill requirements of the type of work being performed for a specific skilled process. Each major process area has similar methods, tooling, equipment, workplace layout, work instructions, and so on, regardless of the product being manufactured.

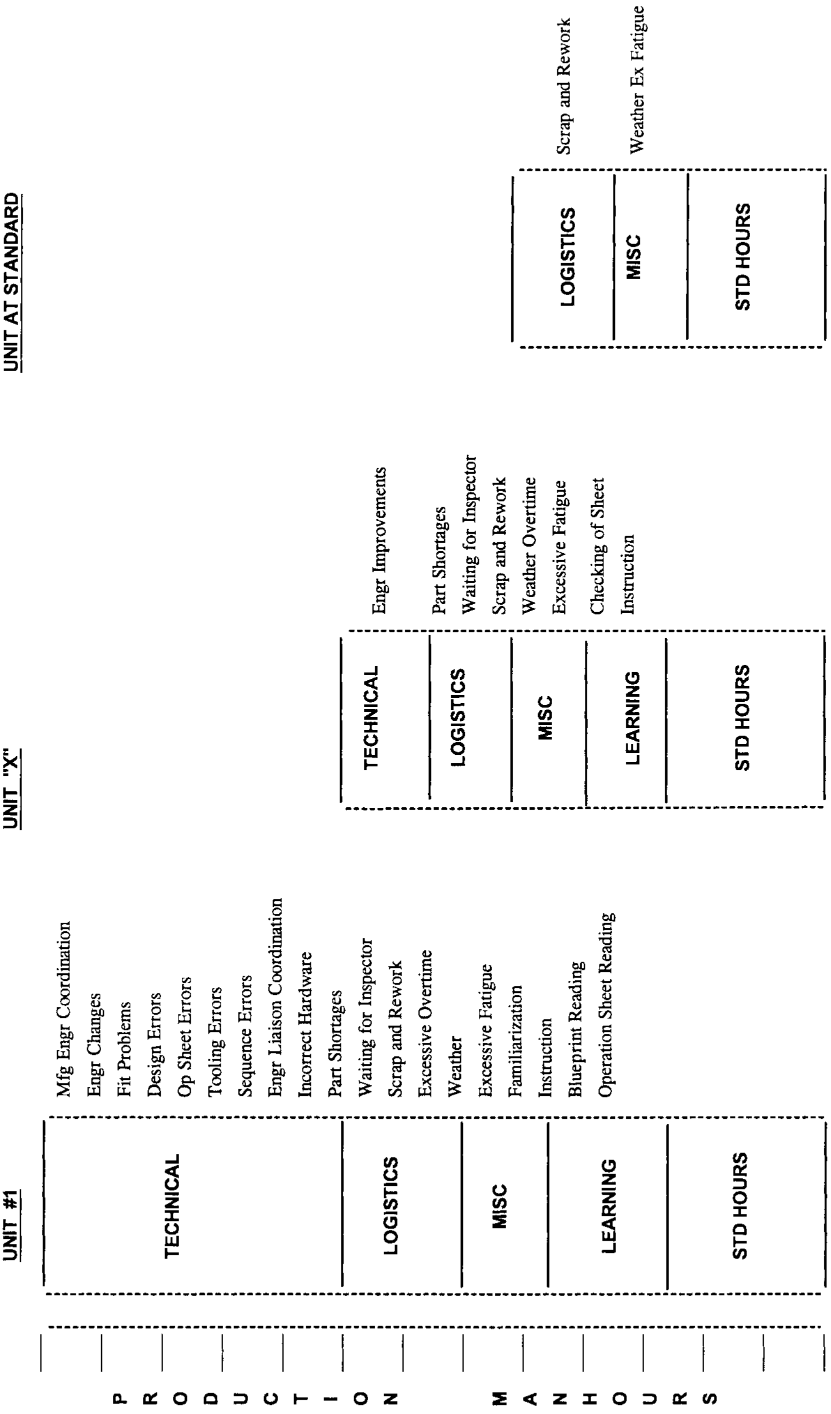
PRODUCTION MANHOURS
UNIT #1
TECHNICAL
LOGISTICS
MISC
LEARNING
STD HOURS
Mfg Engr Coordination
Engr Changes
Fit Problems
Design Errors
Op Sheet Errors
Tooling Errors
Sequence Errors
Engr Liaison Coordination
Incorrect Hardware
Part Shortages
Waiting for Inspector
Scrap and Rework
Excessive Overtime
Weather
Excessive Fatigue
Familiarization
Instruction
Blueprint Reading
Operation Sheet Reading
UNIT "X"
TECHNICAL
LOGISTICS
MISC
LEARNING
STD HOURS
Engr Improvements
Part Shortages
Waiting for Inspector
Scrap and Rework
Weather Overtime
Excessive Fatigue
Checking of Sheet
Instruction
UNIT AT STANDARD
LOGISTICS
MISC
STD HOURS
Scrap and Rework
Weather Ex Fatigue

FIGURE 17.5.5 Improvement curve element.

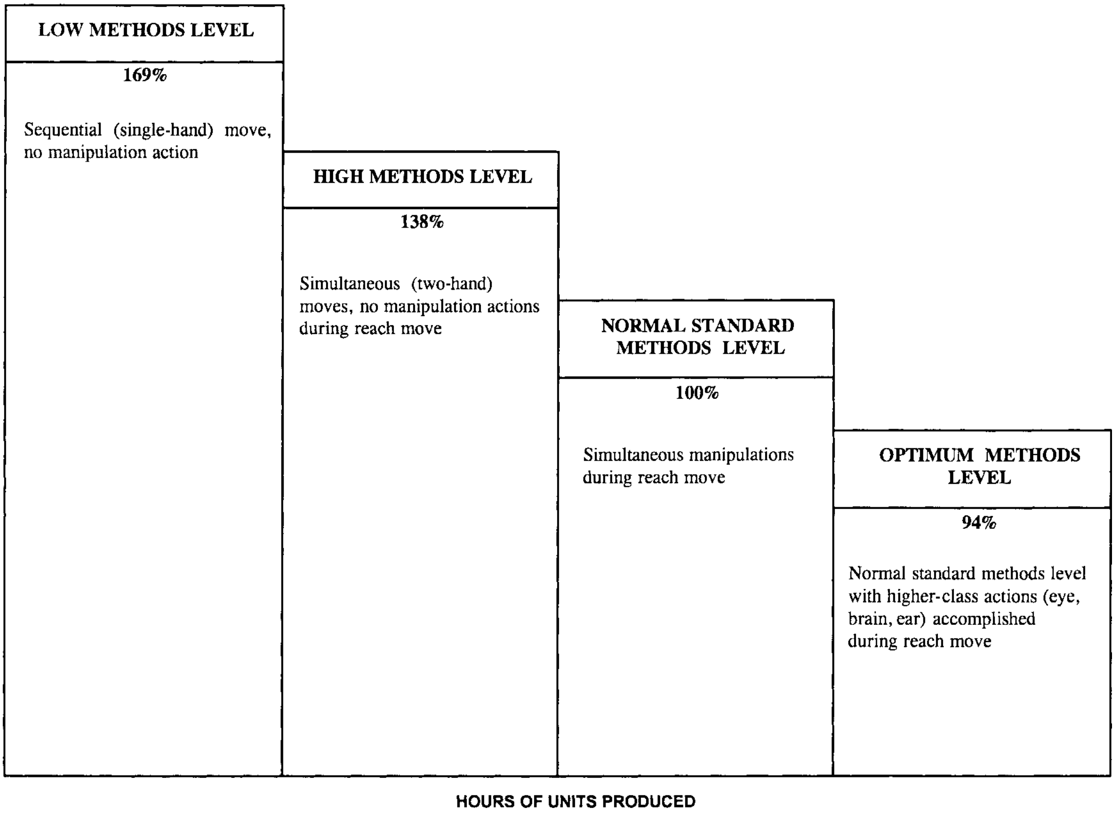

FIGURE 17.5.6 Learning proficiency (MTMI). (*Source: MTM Association raw data.*)

For both product and process familiarity, the complexity of the product, length of cycle time, and the variability of similar products all significantly influence the number of repetitive cycles needed to achieve the level of a fully trained operator on which the standard time is based.

Loss of Learning Due to Breaks in Production Impact. Loss of learning due to a break in production continuity generally occurs more frequently in the aerospace and defense industry than in commercial industry. The commonly accepted Anderlohr theory [6] (see Fig. 17.5.7) recognizes the changes from prior production that occur due to breaks in production involving operator learning and supervisory learning, as well as those changes in methods, tooling, and plant layout that adversely impact achieving prior cost performance. To apply the loss-of-learning factor, one estimates the percentage of learning loss due to (1) operator learning due to forgetting work procedures, hiring of untrained replacement personnel, and rehiring of personnel from layoff; (2) supervisory learning due to transfer of supervisors, limited knowledge of new supervisors, reducing the amount of guidance provided to the worker; (3) continuity of production with resulting physical changes in production lines due to production capacity; (4) method changes resulting from rerouting of operations due to in-plant changes since the last production lot; and (5) tooling differences, including temporary or low-volume tooling versus long-run production tooling, modified tools due to wear, and tooling replacement obsolescence.

Logistics. Logistics elements contributing to failure to achieve standard time include parts availability, manufacturing complexity, production rates and schedules, and machine availability and facility layout.

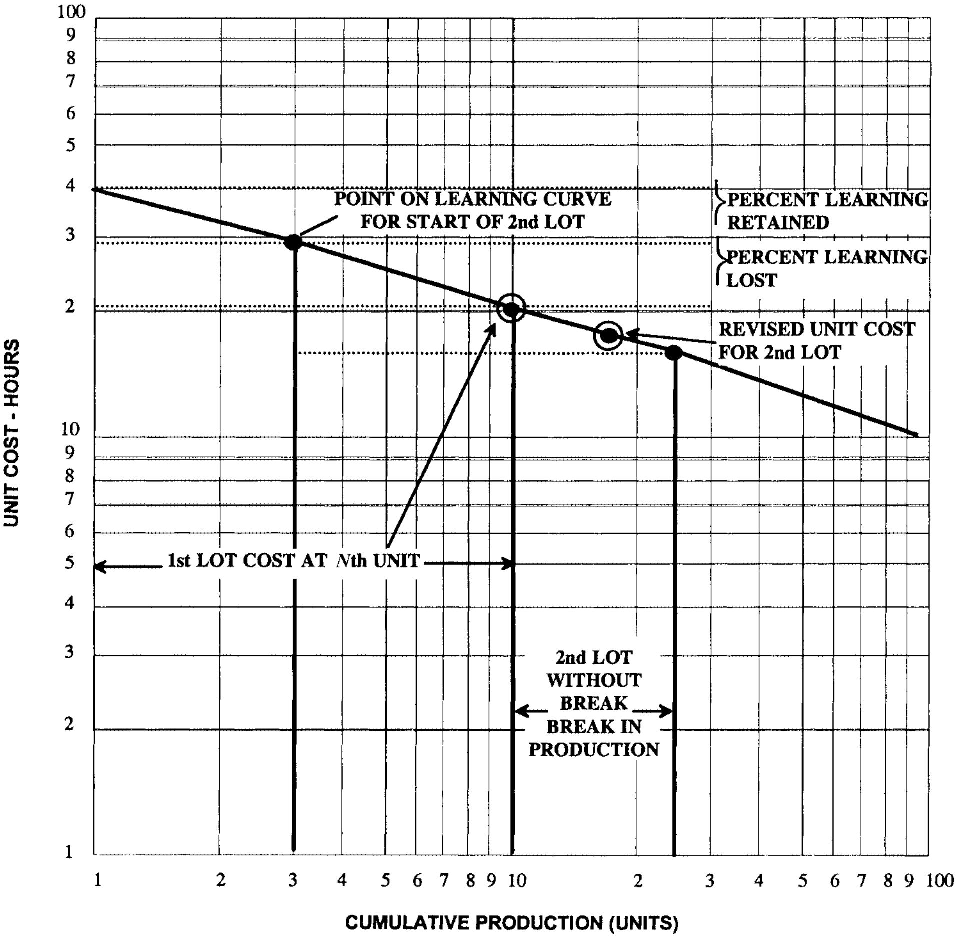

FIGURE 17.5.7 Loss of learning due to product breaks (George Anderlohr theory).

Parts Availability. This is a problem for new or recently developed processes or techniques that take time to settle down into a routine. As the engineering design matures, the impact of design changes and fixes reduces dramatically. During the production cycle, there are times whereby tool breakdowns or wear and tear can impact the continuous work flow. Inadequate time to procure material resources can influence the continuous work flow. Because of the low quantity requirements and more demanding production specifications for parts procured for the aerospace and defense industry relative to commercial industry, suppliers place lower priority on filling aerospace and defense industry needs.

Manufacturing Complexity. Due to the complexity of items produced, there is a high variability in the process yield, which is difficult to forecast. Company and customer inspection personnel availability, where and when required, cannot always be coordinated perfectly with the production mechanic. Effective production control support is necessary to assure the availability of hardware, parts, power/hand tools, assembly tools, and assembly paperwork to achieve standard. The production operation sequence data package must have the necessary specification callouts and operation work instructions that reflect the most efficient operation. This requires added time for reading the appropriate documentation, not always included in the IE-allowed standard time.

Production Rates and Schedules. The coordination of unit cost reduction and production rate buildup must be in concert in order to minimize labor requirement fluctuations. Production cycle variations that increase and/or decrease from a requirement standpoint cause inefficient labor utilization. The stops and restarts of terminations and gaps in the product life cycle cause a relearning process and a loss of progress in continuous learning as expressed in the improvement curve.

Machine Availability and Facility Layout. There are cases where machines unexpectedly break down and/or are not available due to higher schedule priorities, which cause production to move to less efficient machines. Due to the uncertainties of future work, the most efficient plant layout must be developed and reevaluated due to constant changes to avoid congestion, improve work flow, and best utilize space.

Technical. Technical factors contributing to failure to achieve standard time include engineering design changes, planning and tooling, and unclear and/or unrealistic quality acceptance criteria, all impacted by state-of-the-art technology, product complexity, and producibility-related issues.

Engineering Design Changes. Engineering design changes result in tooling changes, process specification changes, product flow changes, worker unlearning and relearning, rework of units/parts built to early configuration, work stoppages pending revised paperwork and components, materials, expendables not available and/or not to specification. These design changes are caused by unpredictable design; tolerance stackups; early startup of production (i.e., prior to completion of design verification); and lack of funding, time, and/or front-end emphasis on producibility versus functionality of the design.

Planning and Tooling. Planning and tooling problems create rework and repair caused by tools improperly designed/built, rework caused by process planning errors/wrong callouts, and alternate/work-around methods (e.g., open setups versus jigs or fixtures, conventional operations versus numerical control, single spindle versus multiple spindle, layout versus templates, labor-intensive operations versus automation and tool liaison interruptions). Planning and tooling changes are caused by schedule, funding, and business constraints. *Schedule constraints* include tools designed from preliminary engineering releases, lead time for tool fabrication, time availability for toolproofing, and inflexibility of schedule changes. *Funding constraints* include producibility review of tool designs, expense tooling budgets, and automation capital availability. *Business constraints* include peaks and valleys in requirements for highly skilled workers in planning, tooling, and first-article inspection.

Unclear and/or Unrealistic Quality Acceptance Criteria. These result in usable hardware being rejected, excessive and/or redundant inspection buy-offs, and added rework and reinspection costs being incurred. These quality changes are caused by a low-confidence factor on new product specifications, unclear product requirement criteria, part and product complexity, process capability versus state-of-the-art designs, and incomplete training for new workers and/or new products and processes.

Miscellaneous. Even if we could control all learning, logistics, and technical elements, there still are times, particularly in the new product startup phase, when excessive overtime is required to meet schedules. Similarly, excessive fatigue, created by excessive overtime and/or having to correct errors caused by others, adds time over and above standard. Also, if there is a snowstorm or some other act of God, people must be paid a minimum number of hours. These costs are sometimes covered in overhead; if they are not, however, they need to be factored in to estimate total expected hours.

ISSUES

Automation

Automation has an impact on learning curves. Typically, the more automated the process, the more controllable, particularly with respect to repeatability. Machine and tool prove-out are additional one-time setup costs, but once the process and method are proven out, there is little learning, except for the person-time component of cost (e.g., materials and tool handling, perishable tool replacement, setup, etc.). Many of the technical and logistic cost drivers impacting the learning curve are controllable by the more automated process. Thus, processes like machining, sheet metal, and robotic assembly approach a 100 percent learning curve, and final assembly and testing of large complex items with long cycle times approaches a 70 percent learning curve.

Product Life Cycle Impact

If one reviewed the learning curve relationships for the full product life cycle of a complex, high-technology new product, it probably would not follow one linear curve. Figure 17.5.8 attempts to graphically describe what most likely occurs. Usually, the learning curve is steeper in the initial production stages due to the technical and logistic cost driver activities, as defined in the section entitled "Learning (Improvement) Curve Elements." It then flattens out in three more stages to the point that only the learning cost driver activities remain. Finally, the improvement curve actually realizes a labor cost growth near the end of its product life as production rate and volume decrease, necessitating process and method changes. Machine utilization and tool repair costs no longer warrant more automated processes. This relationship is highly influenced by: (1) production rate and volume changes; (2) manufacturing methods, tooling, and equipment utilized; (3) product complexity; (4) producibility; (5) value engineering changes; and (6) make-versus-buy decisions.

Step Changes Due to Impact of Future Trends in Product and Process Technology Innovation

Innovation is the only long-term sustainable competitive advantage. It's the only competitive advantage that is adaptable to any situation. It is, after all, what enables an organization to create its products and services and differentiate them from those of its competitors. There is a transformation occurring from an industrial to a knowledge-based society. These innovative product and process changes will have a dramatic impact on learning curve prediction.

One of the best examples of the upcoming innovation impact on manufacturing is the invention of molecular nanotechnology. Molecular nanotechnology is the process of building things from the bottom up—starting with individual atoms and using molecular-sized machines to put structures together in predetermined configurations. Molecular manufacturing will be able to make almost anything with little labor, land, or maintenance, with high productivity, and with modest requirements for materials and energy. Nanomachines will be a prescribed collection of shafts, bearings, cams, articulated arms, pumps, and so forth put together in combinations that function like small factories. This will have a significant impact on replacing most electromechanical devices. Their cost impact will be orders of $\frac{1}{10}$th to $\frac{1}{100}$th magnitude less.

One of the best current examples of innovation impact on manufacturing is the replacement of metal structures with composite material structures. To date, this has been most applicable in the electronics and aerospace industries. Fuselage and wing structure manufacturing processes have been vastly changed by precision layering of composite structures versus metal removal, forming, and joining. In electronics, low-temperature cofired ceramic

LEARNING CURVES

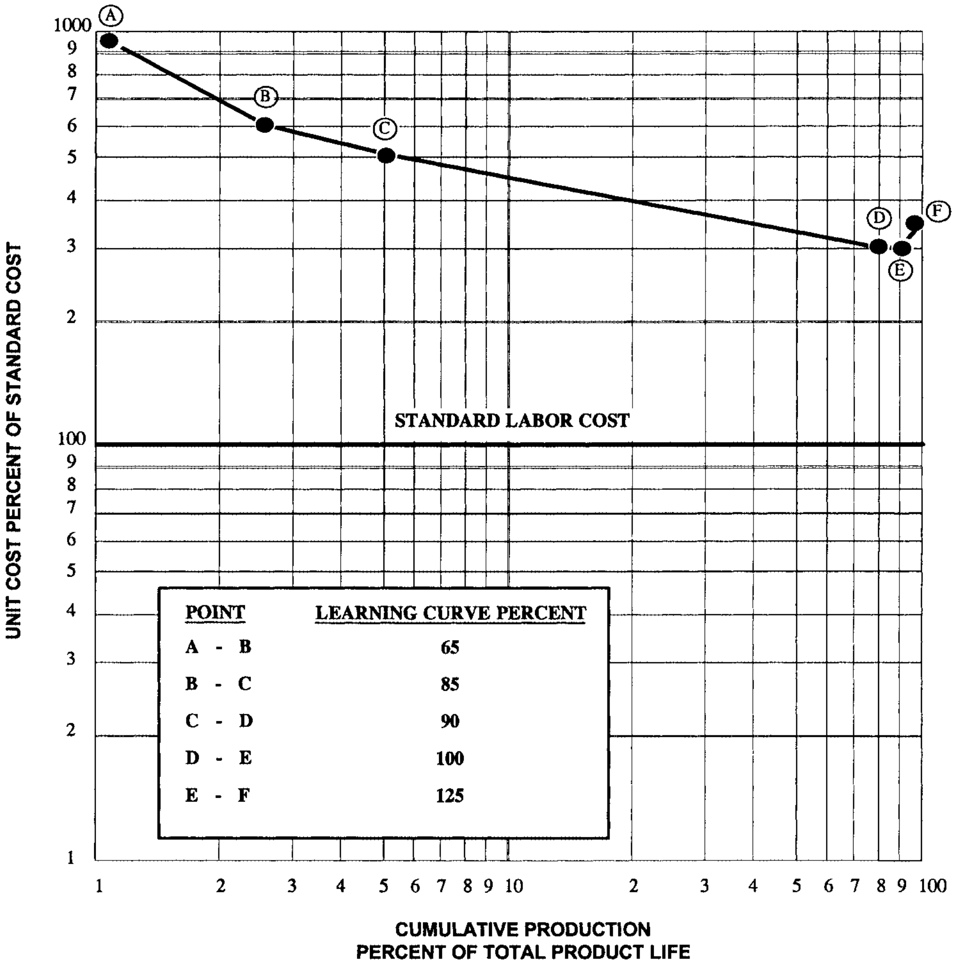

FIGURE 17.5.8 New product overall learning curve, total factory labor and overhead cost (constant dollars).

structures can be formed that eliminate material removal processing and costly interconnect wiring. However, probably the best example of innovation is the impact of semiconductor manufacturing, where the performance of computers has doubled every 18 months while keeping the same cost. Thus, the cost performance of computers has been following a very steep improvement curve.

Step Change Due to Future Trends in Shifting to a Self-Empowered, More Learned Worker

Traditionally, American factory workers have not been expected to think on their own, but only to follow specific instructions from their supervisor or detailed, step-by-step workplace method instructions on how to accomplish the task they have been assigned to. Factory workers have been expected to "leave their brains at home." The future trend is toward the learning organization, recognizing that factory workers have a brain that should be exploited in finding different, more efficient means of performing a task.

Learning organizations are skilled at five main activities: (1) systematic problem solving, (2) experimentation with new approaches, (3) learning from their own experiences and past history, (4) learning from the experience and best practices of others, and (5) transferring knowledge quickly and efficiently throughout the organization. Each is accompanied by a distinctive mind-set, toolkit, and pattern of behavior. From the standpoint of innovation, there are two principle types of learning: single-loop and double-loop. *Single-loop learning* emphasizes the type of association building that results from repetition and routine. The organization is open to its environment, but only in ways that are consistent with its guiding norms and the capabilities of its existing technology. Operator learning is a classic example of single-loop learning.

Double-loop learning involves changing what the organization is doing in terms of its underlying norms and technologies. This is an example of what is occurring in next-generation manufacturing. Double-loop learning will have a significant impact on predicting future cost due to step changes in workforce knowledge, self-empowerment to apply that knowledge, and a significantly more open management/labor working environment in which factory workers will be encouraged to use their brains.

Most companies have been fixing problems on the factory floor as process failure occurs, without taking the time to find the root cause of the problem. One of the first steps to take is to prevent recurrence by developing learning loops to feed information rapidly from the point where problems are discovered back to the point where people can prevent those problems from recurring. Second, one needs to take a more disciplined approach to finding the root cause of the problem. The more knowledgeable the factory worker, the better the chance to resolve problems that prevent one from achieving standard time.

LEARNING CURVE ESTIMATING ACCURACY ASSESSMENT

The accuracy and reliability of estimating factory labor is normally highly dependent upon the previously defined factors:

1. Well-defined and consistently applied methodology
2. Accuracy and consistency of standard time estimate
3. Improvement curve elements—technical, logistics, and learning
4. Automation
5. Product life cycle
6. Next-generation manufacturing technology impact
7. Next-generation manufacturing self-empowered knowledge worker impact

Findings and evaluations point out the need for refinement in all seven areas just identified. There appears to be more of a tendency to understate, rather than overstate, the estimated cost if the stated methodology was used. Measuring the standard time for a short-cycle time application to an accuracy of +5 percent at a 95 percent confidence level is possible. This is especially true if an acceptable predetermined time system is used properly. However, the definition of standard time presupposes the following: a fully trained operator with normal skill, with normal working conditions, working to a prescribed method. And even more important, one needs to "learn" the product and process and to repeat the operation over and over again without a break in continuity in order to achieve standard.

The learning curve phenomenon comprises many variables, most of which contribute to taking longer to perform a standard operation than standard time. Thus, it is considered more of an art than a science to predict the point on the learning curve at which the standard time applies. In addition, the percentage of improvement varies significantly in applying the learning curve theory.

Figures 17.5.9 to 17.5.11 highlight the wide range of unit cost factors for the following widely recognized learning curve assumptions, respectively:

1. Figure 17.5.9, based on various learning curves (85 to 95 percent), with standard base at unit 1000
2. Figure 17.5.10, based on the standard being met at various *n*th-unit quantities (100 to 1000), learning curve assumption 90 percent
3. Figure 17.5.11, learning curves from 85 to 95 percent, point on learning curve applicable from 100 to 1000.

The variability of just the point at which the standard time applies, assuming a 90 percent learning curve relationship, varies from 46 percent at unit 10, to 40 percent at unit 100, to 28 percent at unit 1000. Similarly, the variability of the present learning curve relationship used, assuming the standard time applied to the 1000th unit, varies from 114 percent at unit 10, to 46 percent at unit 100, to no variance at unit 1000.

The overall variability of these two parameters, when combined, varies from 150 percent at unit 10, to 70 percent at unit 100, to 66 percent at unit 1000. Table 17.5.2 summarizes the unit cost factor (realization factor) for unit 1, based on the same overall parameters defined previously.

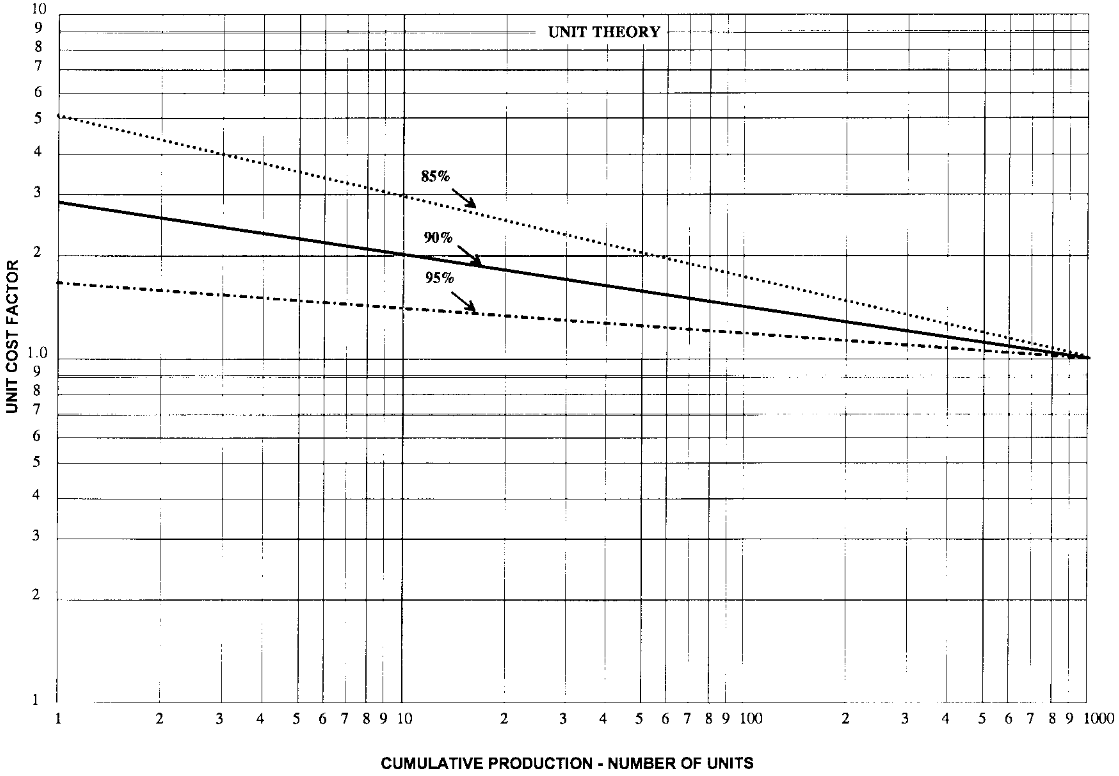

FIGURE 17.5.9 Unit cost factor comparison, variance learning curve (standard at unit 1000).

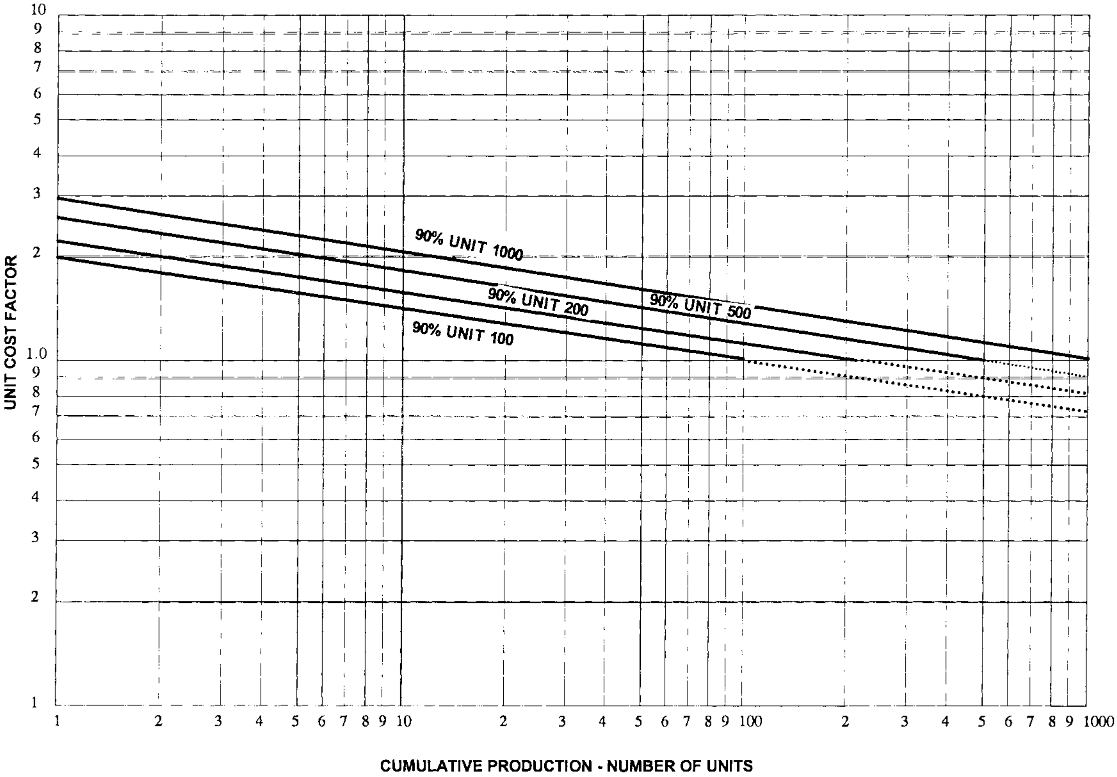

FIGURE 17.5.10 Unit cost factor comparison, standard at *N*th quantity level (90 percent learning curve).

In addition, there is further potential variability in being able to consistently estimate the break-in-production continuity impact on loss of learning. Similarly, the same is true for determining the impact of change in production rate and volume.

In summary, there is a significant degree of vulnerability in trying to accurately estimate factory labor, when considering all of the factors described earlier. However, fortunately, factory labor is rapidly becoming a relatively small percentage of the inventory cost of sales in today's systems. Total manufacturing hands-on direct labor, including test and inspection, typically accounts for only 5 to 15 percent of total direct cost of sales. Manufacturing overhead, again for factory, test, and inspection labor, typically accounts for 10 to 30 percent of the direct cost of sales.

LEARNING CURVE APPLICATIONS

The most significant application of learning curves is in estimating future costs. T. P. Wright noticed a predictable cost reduction (improvement) rate in which the cumulative unit cost decreased by a constant percentage as the cumulative quantity increased by another constant percentage. Initially, most people related this learning curve phenomenon to improved worker performance due to repetition of performing the same task over and over again. However, more modern-day theory recognizes cost improvement is mostly due to contributions

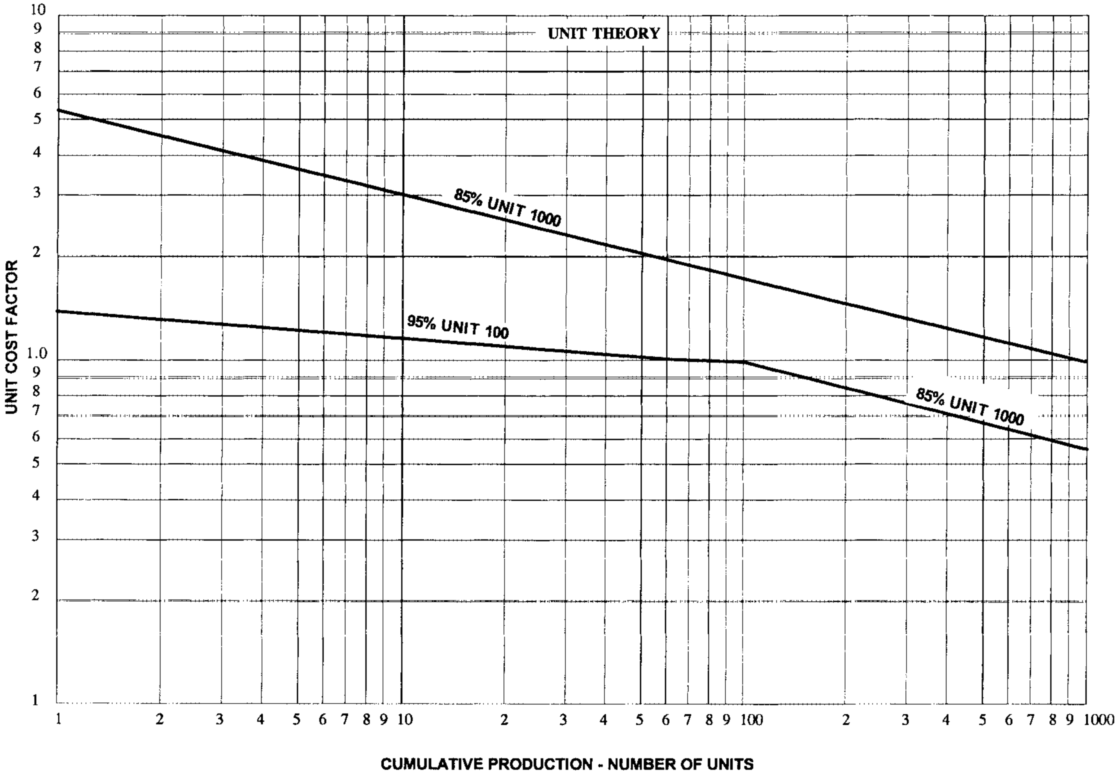

FIGURE 17.5.11 Unit cost factor comparison, learning curves 85 to 95 percent point on learning curve applicable from 100 to 1000.

from management, engineering, and other support departments to attack the other factors rather than the operator, and product and process learning—namely, the technical and logistics factors. Figure 17.5.5 highlights the activities that need to be eliminated, or at least significantly reduced, if one wants to ultimately achieve standard time.

The learning curve is really a mathematical, graphical, or tabular representation of how resources are reduced as production of a product is repeated. Thus, the learning or improvement curve is used mostly to predict production costs from known historical costs of produc-

TABLE 17.5.2 Unit Cost Factor for Unit One

	Cumulative production unit at which standard applies			
Learning curve percent	100	200	500	1000
85	2.94	3.46	4.29	5.05
88	2.34	2.65	3.15	3.58
90	2.01	2.24	2.57	2.85
92	1.74	1.89	2.11	2.30
95	1.41	1.48	1.58	1.67
97	1.22	1.26	1.31	1.35

ing products. The unit of measure is typically unit hours of worker labor required. However, materials cost, facilities floor space, energy, and the like can be similarly estimated when quantity of repetition improves performance.

In manufacturing, industrial engineers are used to plan labor needs, estimate expected actual labor performance (hours/unit), establish sale prices and make/buy decisions, judge wage incentive payments if applicable, evaluate organizational efficiency, evaluate capital equipment proposals, create more accurate production delivery schedules, and estimate new product startup costs to be amortized to the standard cost of product. In the aerospace and defense industry, improvement curves have been used extensively to estimate future product unit hours. Knowing that the first unit was 9.65 times greater than standard time and what percentage learning curve performance had been realized (83.1 percent), then one can predict the expected realization factor of 4.33 times standard time:

$$\begin{aligned}
\mathrm{RF}n &= \mathrm{RF1} \times \text{quantity (log lc/log 2)}\\
\mathrm{RF20} &= 9.65 \times 20\ (\log 0.831/\log 2)\\
&= 9.65 \times 20\ (-0.0804/0.3010)\\
&= 9.65 \times 20\ (-0.2671)\\
&= 9.65 \times 0.4493\\
&= 4.33
\end{aligned}$$

Similarly, if the first unit realization factor is not known, but historical costs indicate that product A is taking 3.9 times standard time at the 50th unit (assuming an 83.1 percent learning curve), then one can solve for what unit 1 would take (11.09 times standard time).

$$\begin{aligned}
\mathrm{RF1} &= \mathrm{RF}n\\
n\ (\text{log lc/log 2}) &= 3.9 \div 50\ (\log 0.831/\log 2)\\
&= 3.9 \div 50\ (-\,0.804/0.3010)\\
&= 3.9 \div 0.3518\\
&= 11.09
\end{aligned}$$

These two examples are plotted on simple graph paper (Fig. 17.5.12) to show the effect of realization factor forecasting.

CONCLUSIONS AND FUTURE TRENDS

The next-generation manufacturing (NGM) [7] vision of rapid and unpredictable change recognizes the effect of *step changes* in the learning curve dramatically impacting learning curve theory. Lot sizes of 1 or less than 10 should be commonplace in the future but most customized products will be only slight variations of a product within a product line family. Development of new materials and technologies (e.g., composites, molecular nanotechnology, biotechnology, and information technology) will have a revolutionary impact on the traditional metal working industry. Through improved process design and automation of manufacturing processes, little if any setup or learning will occur. The transition to self-empowered knowledge workers, operating in an integrated-product-and-process-development team environment, will also have a significant impact on the application of traditional learning curves.

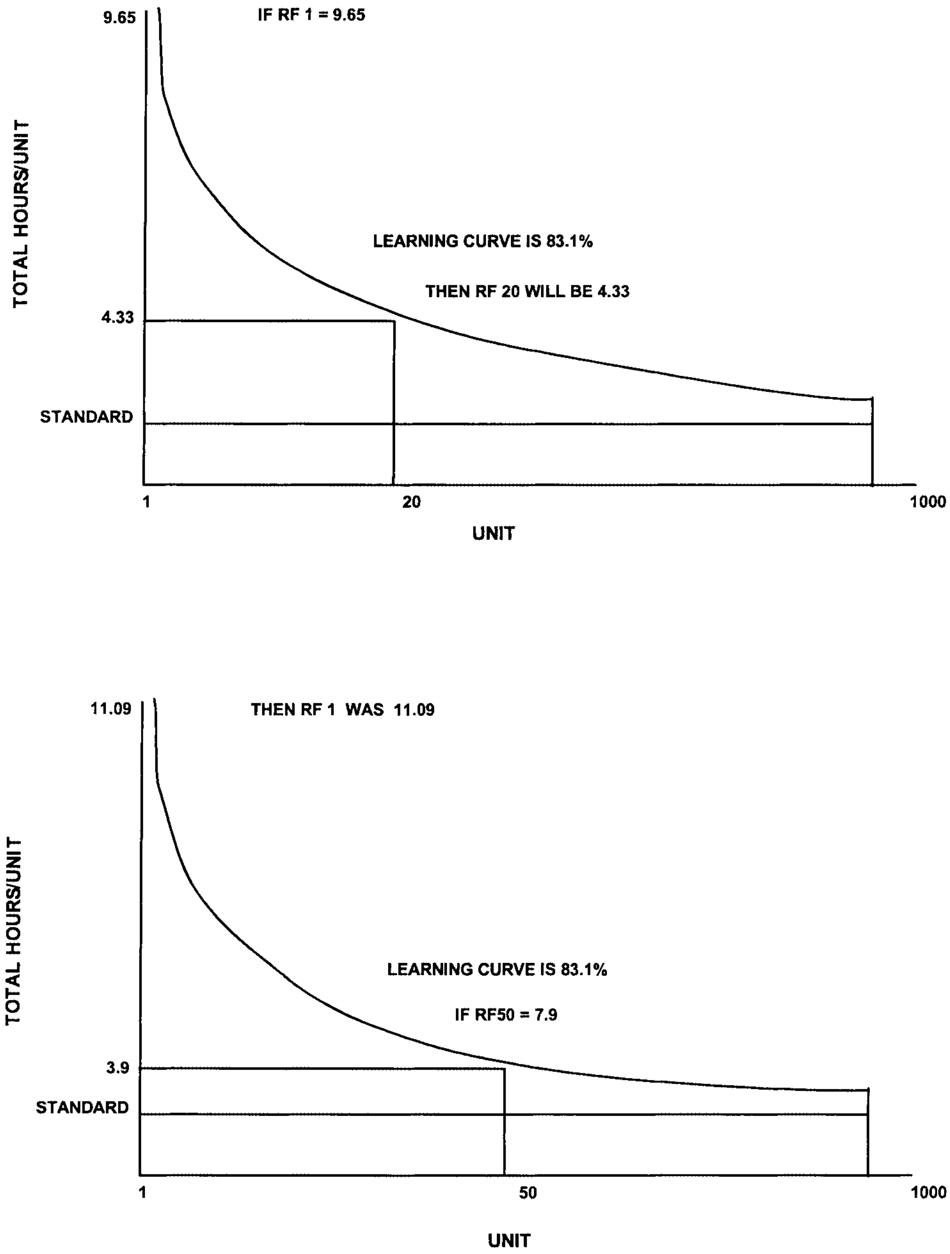

FIGURE 17.5.12 Realization factor forecasting.

The ubiquitous availability and distribution of information, accelerating pace of change in technology, rapidly expanding technology access, as well as knowledge workers, provide an opportunity to significantly change the way we manufacture goods. The next-generation manufacturing company will employ an ever-growing knowledge base of manufacturing science to implement reconfigurable, scalable, cost-effective manufacturing processes, equipment, and plants that adapt rapidly to specific production needs. A systemic holistic approach of integrating people, business processes, and technology is essential to making step function improvement. Factory workers will become more knowledgeable and will be required to bring their brains to work and use them.

Thus, in the future, the use of standard time–based learning curves and factory worker–detailed work measurement will decline substantially. However, the need for measuring overall tactical process performance improvement will increase in order to ensure meeting an organization's strategic goals and objectives. The need to forecast an organization's resource requirements will still be there, not just for factory hands-on workers, but for all key skilled resource needs. Thus, more aggregate-level improvement curves based more on actual costs than factored standard times will be emerging.

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BIOGRAPHY

Richard L. Engwall has been in his own management consulting business for the last five years. His focus is on strategic business planning, manufacturing/engineering integrated product process development (IPPD), enterprise integration, cost/performance management/control and manufacturing research and development. Prior to consulting, he spent 17 years with the Westinghouse Electronic Systems Group, most recently as Manager of Advanced Manufacturing Initiatives, responsible for advanced manufacturing technology R&D contracts, and development and implementation of an overall strategic manufacturing strategy. Prior to Westinghouse, Mr. Engwall had 23 years of varied manufacturing, engineering, marketing, and general manager management experience with a variety of major blue-chip companies in mostly commercial industries. He holds an M.B.A. in production management and a B.S. in industrial engineering from Northwestern University. He is a fellow in the Institute of Industrial Engineers, senior member of the Society of Manufacturing Engineers, and has been very active in a number of industry associations associated with the aerospace and defense and electronics industries. He was the industry spokesperson for the U.S. Senate hearings on work measurement conducted in 1985, which is the foundation of much of the content in this chapter.

CHAPTER 17.6

GROUP TECHNOLOGY

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Where, despite the visibility of mass production, low quantity production still represents between 50 and 75 percent of all manufacturing, methods have been developed to improve the efficiency of low quantity production. The similarities of parts, either from a design or a manufacturing point of view, can be used for design and manufacturing standardization, which in turn can lead to cell manufacturing. This technique is called *group technology.*

HISTORY AND BACKGROUND

While the introduction of the steam-driven engine in the nineteenth century is most often recalled as the major step forward in the Industrial Revolution, there were many other developments that have contributed to modern manufacturing as we now know it. For example, the early 1920s were highlighted by steps in the optimization of design and manufacturing processes for mass production on a great scale. When hundreds of thousands or millions of units are being produced, a very small change in efficiency can lead to a very great gain in cost savings.

In recent years, there has been a steady stream of improvements in the technology of mass production, many of them enabled by the emergence of computerization. The quality of everyday life in the second half of the twentieth century would have been much different without these optimized mass production processes.

We do not live in a mass-produced world, however. In fact, most of the things we have and use are not made on assembly lines. They are produced in relatively small batches. Even in the United States and other highly developed industrial nations, approximately 50 to 75 percent of all manufacturing is done in batches—in lots ranging in size from one or two to a few thousand.

Despite its importance, very little was done to improve batch manufacturing during the first half of the century. A major problem was the seeming randomness of both design and manufacturing activities in the batch environment. Without readily apparent consistent patterns in these activities, it was difficult to even define approaches to their optimization.

There have been other discouraging factors. While there has been an increased awareness of the problems of batch manufacturing since World War II, its importance has been questioned. The consensus has been that batch manufacturing would decline in importance and that more and more items would be produced in mass production environments.

That has not been the case, however. There has been a movement to smaller and smaller lot sizes, influenced by government regulations, energy costs, demands for more personalized products, and widespread marketing trends. The fact is that batch manufacturing is probably more important now than it has been since the introduction of the assembly line.

Recognizing the need and its importance, some attempts have been made to improve the state of the art from time to time. They have met with varying degrees of success. Most were somewhat limited and never had a great impact. Others proved to be useful in some applications. Dealing with logistics, for example, there were some successes in the development of queuing and sequencing programs. There was also some standardization of certain design and manufacturing activities, and some types of quality issues were addressed with numerically controlled tools.

More might have been done, but the economics did not appear to be encouraging. It was difficult to justify large investments for research and development into operations that were perceived to be dedicated to producing small lots: a half-dozen gears, a few washers here, a few shafts there, and so forth. When something was to be produced in the millions or tens of millions, a fraction of a penny shaved from the cost of each unit would yield sizable savings. When dealing with small lot sizes, the total savings might be no more than pennies. Since batch manufacturing was equated with small-lot-size production, there was little motivation for expensive research and development.

Looking at the Bigger Picture

The key to effective investment in solutions to batch manufacturing problems is a matter of perspective. To be cost-effective, solutions need to be focused on the ways that virtually all design and batch manufacturing are carried out, not on low lot-size products. Solution developers need to look at principles more than products.

Given the random nature of batch manufacturing, the identification of these principles has not been easy. There have been significant advances in the search for areas that could be improved, and in the development of approaches that have resulted in their improvement.

There are now material requirements planning systems and enterprise resource planning systems that greatly improve manufacturing and information processes. They are very expensive, however, and are thus beyond the means of most small companies. There are other, perhaps more appropriate, approaches to improving batch manufacturing efficiencies.

Recognizing Part Similarities

If you were to ask the production manager of a typical batch manufacturing facility whether there was much similarity in the parts that he or she produced, the chances are that you would be told there were virtually none—every product is different.

For example, a maker of steam turbines would probably tell you that since each turbine is designed and manufactured to individual customer specifications, each one is obviously different. From an outsider's point of view, however, the differences may appear to be primarily matters of size. Many of the components—impellers, shafts, and the like—look more or less alike. Centrifugal pumps are another example. While there may be many different pump types, many of the parts and subassemblies are much the same. The same is true in the manufacture of airplanes, machine tools, and many other mechanical, electrical, or electronic products—while there may be many differences in the ultimate product, many of the parts and part combinations are the same.

The fact that there are such similarities is obvious—even a simple set of products share common types of screws, pins, washers, shafts, and other parts. Complex constructions such as airplanes can share millions of common parts. Recognizing the concept of similarities is one thing; being able to do something with them is another, however. Some responses are relatively easy and not uncommon. A supervisor on the shop floor might organize the sequence of parts awaiting production on a given machine tool to help minimize the setup time required to produce those parts, for example. On a larger scale, recent developments include flexible manufacturing systems based on part similarities.

Defining Similarities

In the past half-century or more, two different approaches to dealing with similarities have evolved. On the one hand, one could look at parts in terms of their *design similarities* (see Fig. 17.6.1). Grouping them according to these similarities provides a rationale for a retrieval system that enables designers to take advantage of some of the features of previous designs to create new ones. In the 1930s and 1940s, design-based types of retrieval systems were developed and were, in certain industries, quite successful. They were called *design-based classification systems.*

The other approach—*manufacturing-based classification*—began to evolve in the 1940s. It is based on the idea that parts do not have to look the same to be similar. Although they may appear to be different, they can be manufactured in the same way—with similar routings across the same machine tools. As a result, it becomes possible to develop a classification system that groups parts according to their manufacturing characteristics. Figure 17.6.2 illustrates examples of parts that are different from a design or functional point of view, but are quite similar in manufacturing terms.

Using such a manufacturing-based classification system, designers and manufacturing engineers can organize families of parts that can go through the same manufacturing processes together. It also becomes possible to retrieve the best manufacturing methods for members of part families.

A Case in Point

A case in point is a recent survey at a world-leading steam turbine manufacturer. Prior to the survey, the production manager assured researchers that each steam turbine was entirely different from the next one, and that no manufacturing method was similar to the previous one.

An extensive analysis of the company's manufacturing processes revealed that its parts comprised no more than approximately 20 to 25 different geometrical (shape) attributes—holes, slots, cylinders, pockets, flats, threads, and so on. Looking further, the analysis indicated that there were approximately 20 to 30 different manufacturing methods per attribute—the use of different manufacturing methods for the same attribute was based on factors such as the size of the parts, the material choice, the tolerances specified, and lot size. In other words,

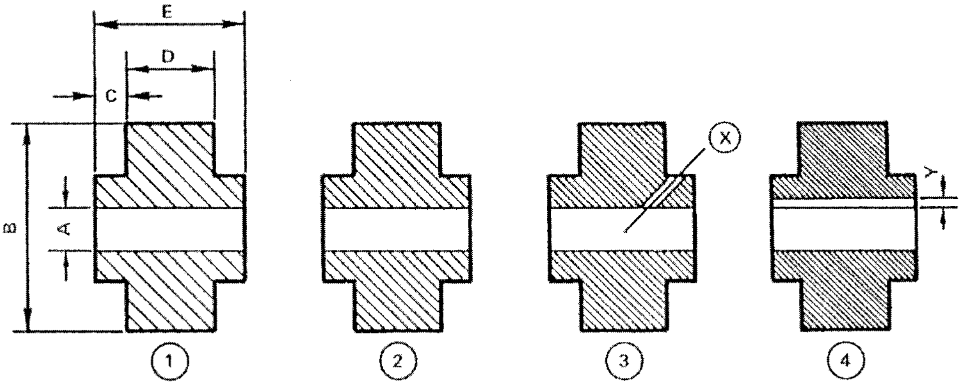


FIGURE 17.6.1 Similar parts from a design point of view.

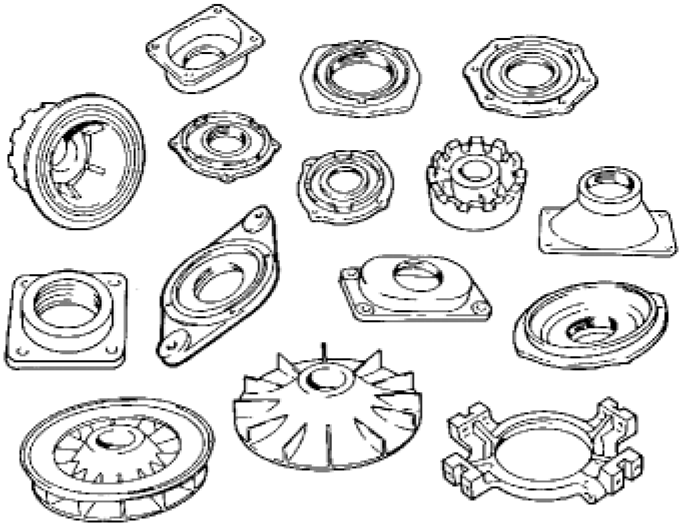


FIGURE 17.6.2 Similar parts from a manufacturing point of view.

the differences in actual manufacturing were far less than perceived by the manufacturing manager.

Furthermore, the fact is that there are only a limited number of different types of machine tools, and each can only perform a limited variety of operations. The finiteness of attributes is, in fact, limited to the machines available on any shop floor.

In general, there are limitations to the number of shapes designed and to the number of manufacturing methods used in a factory. If one looks at the design attributes of parts being released to the shop floor or to the manufacturing engineering department for manufacturing planning, the limitations become quite obvious. As Fig. 17.6.3 illustrates, the number of shapes released for manufacturing (vertical curve) versus the total number of parts released (horizontal) flattens after only approximately 10 percent of the annual production of parts. In other words, no matter how many different parts are designed in a company each year, a random selection of 10 percent of the parts released in a year will generally be enough to encompass all of the different shapes and attributes to be found in the company's total parts population. Similarly, one can do the same for new manufacturing methods. A random selection of about 10 percent of parts released for manufacture in a year will represent virtually all the manufacturing methods being used in that company.

The Basis for Group Technology

The fact that there are limits in both design and manufacturing variety provides a basis for the concept of group technology. It has evolved as an approach to dealing with both design and manufacturing optimization. In essence, *group technology* can be defined as a consistent method of grouping parts with similar design or manufacturing features together and then developing standards for the future retrieval of these groups and their members. On the design side, its applications include design retrieval and the development of design standards for selected groups of families of parts. Manufacturing can use it to create standards for producing parts that utilize common manufacturing methods, and—by examining past experience—for optimizing these methods for families of parts.

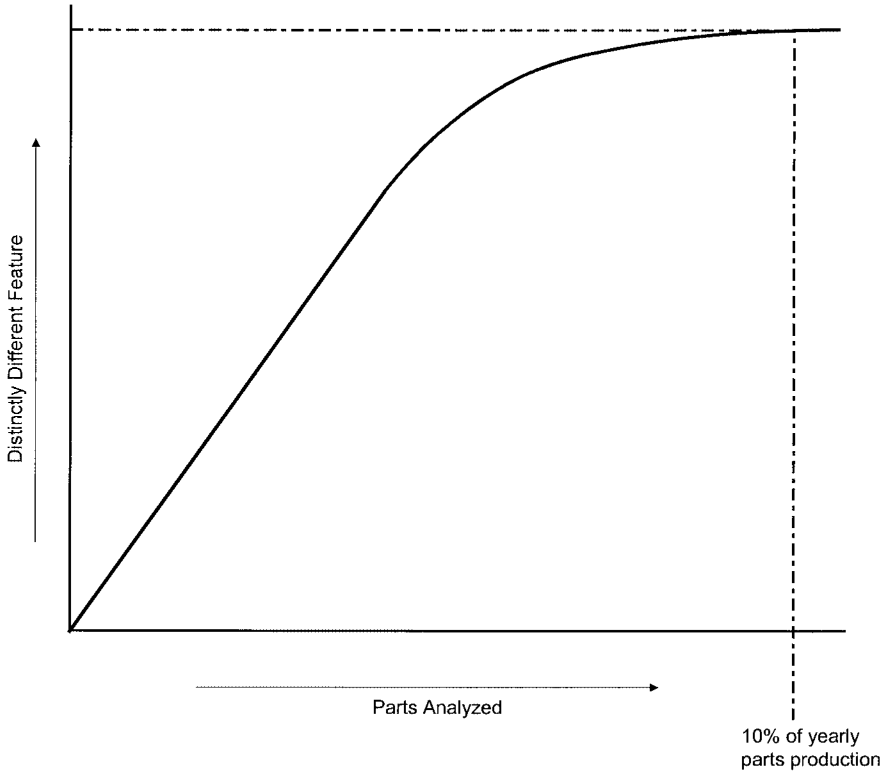


FIGURE 17.6.3 The number of distinctly different features produced in a company is small.

The Benefits of Group Technology

Since manufacturing costs are the major determinants of ultimate product costs, it is not surprising that optimizing the manufacturing process by grouping parts together can produce a significant return on investment. Consequently, grouping of parts that are made with the same or similar manufacturing methods is an attractive concept, and it can drive a design standardization process based on best manufacturing processes.

By analyzing the database, it is possible to identify groups of parts that are similar from a manufacturing point of view. Having done that, the next step is the standardization—by manufacturing engineers—of manufacturing processes for groups of similar parts. This manufacturing standardization then leads to a *best-practice* approach to making parts, and it provides the basis for part-making instructions to the shop floor.

The grouping of parts into families can lead to the development of a new type of mass production and the introduction of mass production methods for those families of parts. So in reality, the costs associated with classification and standardization do not have to be applied to lot sizes of two or three, they can be written off to families of parts that may run in much larger numbers. Consequently, people sometimes refer to group technology as a form of *poor person's mass production.*

In fact, grouping can lead to the types of economies normally associated with mass production, even in such advanced manufacturing environments as aerospace and defense. For example, the production of a class of aircraft may involve very similar procedures for making and assembling the parts that go into a door or for assembling a landing gear. The savings involved can be very significant, especially when computers are being used to analyze parts and to feed manufacturing-based design standards to the engineering office's computer-aided design activity.

As an example, consider the design and manufacturing of machines that automatically assemble or help to assemble components such as automobile doors or frames. Each of these machines was individually designed because, although all doors are functionally the same, their designs are slightly different for each automobile type. It was thus logical to assume that the machines that make them must also be different. Under this assumption, the manufacturer's engineering department dealt with each unit as a one-of-a-kind scratch design that required one-of-a-kind manufacturing.

However, when approximately 10 percent of the 15,000 different parts that were designed and manufactured in the course of a year were analyzed, it was found that approximately 75 percent of them could be placed in 22 different manufacturing groups. By standardizing the manufacturing process for each of these groups, the manufacturing engineering department alone was able to improve its efficiency by over 100 percent.

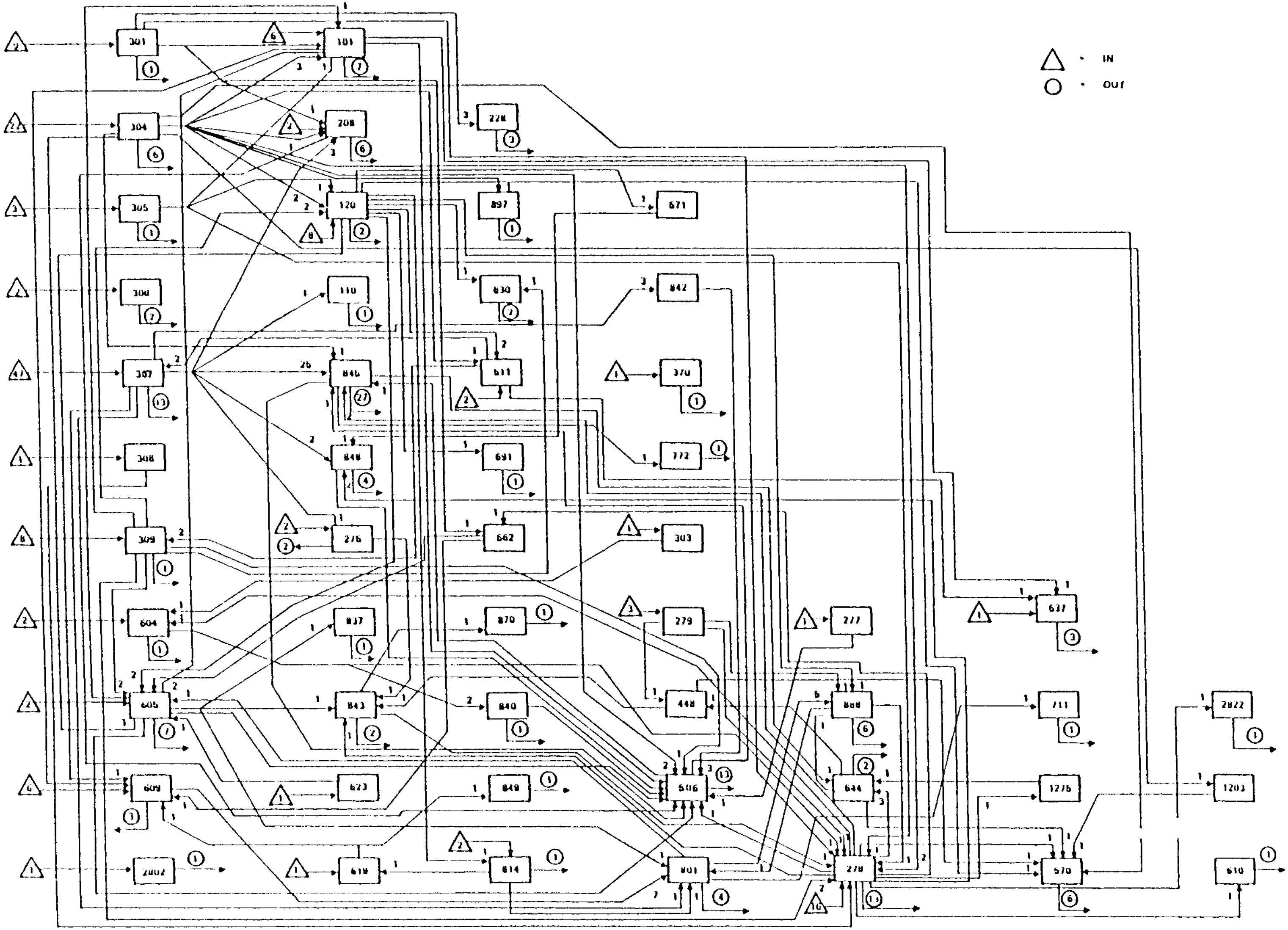
The efficiency flowed downstream. Because manufacturing approaches utilized proven, standardized processes, the instructions sent to the shop floor were clearer and the entire manufacturing process was made more efficient.

Standardizing Routings. Using an example based on a company's experience with the production of 150 very similar parts, the benefits of routing standardization are illustrated in Figs. 17.6.4 and 17.6.5. Figure 17.6.4 illustrates how the 150 parts were routed through the factory before standardization. After a thorough analysis of the design and manufacturing attributes of these parts, the "spaghetti bowl" of manufacturing routings was reduced to a much simpler, much more mass production–oriented flow, as illustrated in Fig. 17.6.5. The parts would now enter a single manufacturing cell at three different locations (identified as entries 78, 12, and 46). Combining three different groups of parts in the single cell made it possible to use the different machine tools very efficiently. The cell could thus work at full capacity.

The Role of Design Standardization. If manufacturing standardization is to be successful, a measure of design standardization is also required. To take effective advantage of optimized best-manufacturing practices, the design department must keep part designs within a range that does not deviate excessively from the group standard. For example, certain shafts in a group may have consistent tolerance requirements. If one designer decides to ignore this standard and arbitrarily increases the tolerance requirement for a particular part, the part might no longer fit in the group. This would diminish the cost-effectiveness of standardized manufacturing, and if done on a large scale, would end the standardization effort. Unfortunately, this happens all too often, particularly since engineering and manufacturing people are not always willing to agree on common standards.

Manufacturing Capacity. Once manufacturing standards have been developed for the limited number of families, the scope of the work can be extended to a major portion of the parts being produced in the facility. In doing so, it becomes possible to extend the benefits of group technology to manufacturing capacity planning. The process is straightforward. The number of hours per month required to produce a family of parts on each machine tool can be calculated—so many hours of a machine tool for turning, so many for milling, drilling, and so on. Because the design and manufacturing processes for the family are known, it is also possible to specify the sizes of the machine tools needed to do the job, and to dedicate specific groups of machine tools, or cells, to manufacture specific groups of parts.

Flexible Manufacturing. Furthermore, once a cellular manufacturing approach has been evaluated, it may be possible to take another step: the design of a flexible manufacturing system.


IN
OUT
301
101
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208
228
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120
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671
300
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842
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846
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691
772
309
276
662
303
604
837
870
279
277
637
605
843
840
448
888
711
2822
609
623
849
616
644
1276
1203
2002
619
814
801
278
570
610

FIGURE 17.6.4 Conventional routing of 150 very similar parts.

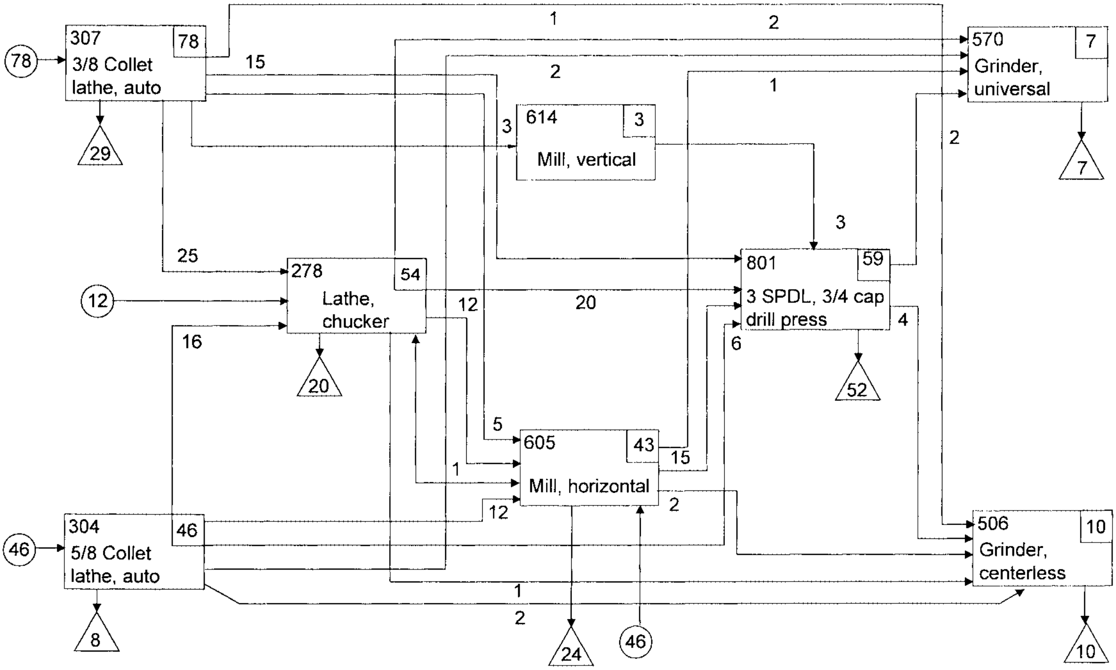
307
78
3/8 Collet lathe, auto
78
29
15
1
2
570
7
Grinder, universal
2
1
614
3
3
Mill, vertical
2
7
3
25
278
54
Lathe, chucker
12
12
20
801
59
3 SPDL, 3/4 cap drill press
4
6
16
20
52
5
605
43
15
1
Mill, horizontal
2
12
304
46
46
5/8 Collet lathe, auto
506
10
Grinder, centerless
1
2
8
24
46
10

FIGURE 17.6.5 Routing of 150 very similar parts *after* group technology analysis.

- 150 parts out of 832 (18 percent)
- 31 flows instead of 87

The investment in such a system is very substantial, and therefore accurate planning is critical. Manufacturing standards must be precise and realistic, and the capacity required to handle the families of parts coming across the shop floor must be carefully calculated.

A successful flexible manufacturing system has several requirements, including design and manufacturing standardization, cellular capacity planning, and an assurance that the savings to be realized will more than offset the expense of setting it up. Appropriate standardization and accurate capacity planning are critical.

How to Get to Groups of Parts

It is one thing to speak of groups of parts that comprise the same array of attributes (holes, slots, etc.). It is another to find them.

During the last 50 years, different methods were designed to separate, or classify, parts into groups that share the same attributes. These classification schemes used numerical or alphanumerical structures for the retrieval of parts in the same class. Several different numbering, or coding, structures were used.

Coding Structures

The classification systems developed in the 1940s, 1950s, and 1960s were based on two types of structures: *hierarchical* and *attribute-based.* The latter were sometimes called *polycode.*

In a hierarchical structure (Fig. 17.6.6), each position relates to the previous position in the code number. Thus, if the first digit defines a main shape, such as rotational, the second digit will define a feature related to the rotational attribute. The meaning of the next digit will depend on the meaning of the second digit, and so on. Since each digit provides more detail about the information contained in the previous digit, it becomes possible to group parts with increasingly specific feature definition as you proceed down the hierarchy. Because it is possible to include a great deal of information in a few digits, hierarchical codes are very compact. They are very useful in highly customized applications and work well in manual environments, particularly for design retrieval. The library applications of the Dewey Decimal system offer excellent examples of a hierarchical code's utility.

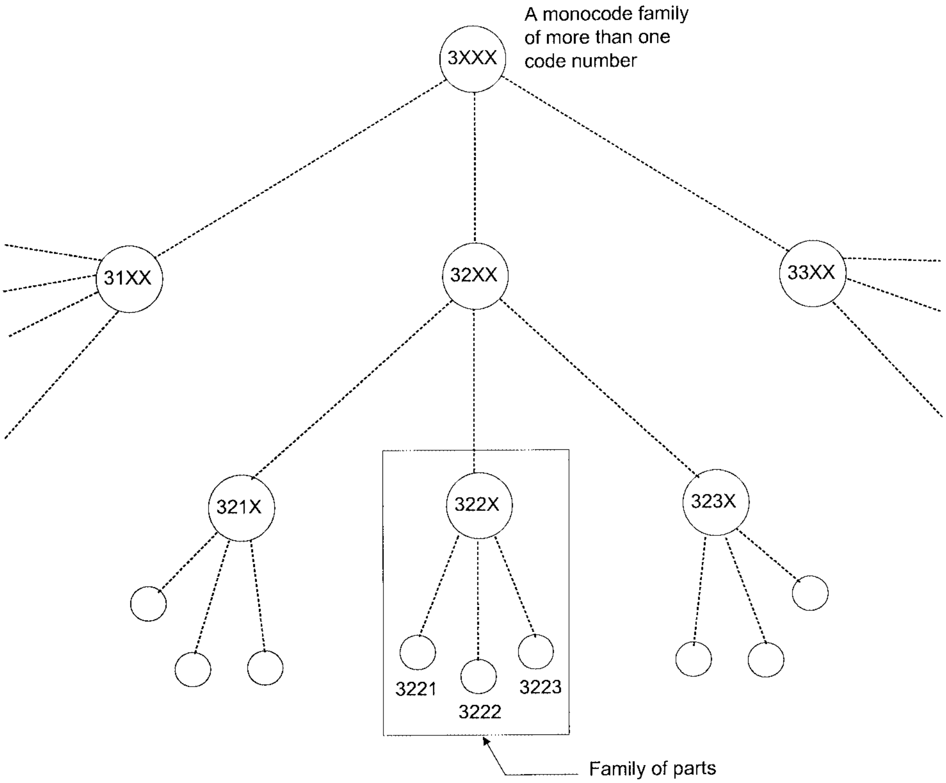

FIGURE 17.6.6 The structure of a classification and coding system based on hierarchical principles.

Attribute codes, or polycodes, are based more on the total population of different attributes. As indicated in Fig. 17.6.7, each position and each digit have a specific meaning. Thus, for example, the first position might always be reserved for external shape, the second for internal shape, the third for the number of holes, and so forth. The external shape would be identified by the digit in the first position, the internal shape by the digit in the second position, and so on. In such a scheme, the complete code number identifies all of the part's major attributes. This type of code structure opens the door for detailed computer analysis, especially in a relational database environment.

		Possible values of digits							
Digit	Class of feature	1	2	3	4	5	6	7	8
1	Ext. shape	Shape1	Shape2	Shape3	—	—	—	—	—
2	Int. shape	None	Shape1	—	—	—	—	—	
3	No. of holes	0	1–2	3–5	5–8				
4	Type holes	Axial	Cross	Axial and cross					
5	Flats	Ext.	Int.	Both					
6	Gear teeth	Spur	Helical						
7	Splines								

FIGURE 17.6.7 Polycode structure.

In order for these classification and retrieval systems to work properly, the rules governing the assignment of parts to groups have to be rigorously enforced. If a part is put into the wrong group, it would be lost forever as far as retrieval is concerned.

Things began to change with the advent of interactive computer systems in the mid-1960s and 1970s. New systems were developed that were based on principles initially introduced in the 1930s and 1940s. Using computers, parts were classified in an interactive process and the data was stored for future retrieval. When retrieved, part descriptions included design and manufacturing method details. Part designers and manufacturing engineers were thus able to take advantage of company experience, and to reapply design approaches and manufacturing methods that had been developed and deemed to be useful and economical in the past.

Taking Advantage of New Information Technology

Information technology has progressed a great deal in the 1990s. Cumbersome manual classification systems are no longer needed to enable the formation of part families. The job can be done well with the use of computer graphics-based attributes classification technology, coupled with relational database systems. By linking a part number to the part's attributes in a relational database, it becomes possible to identify relationships of parts that share similarities.

THE PROBLEMS

Given the potential advantages of the concept and the emergence of the interactive computer, there was a flurry of group technology efforts in the late 1970s and early 1980s. Despite the potential, however, there were problems associated with the use of classification systems that discouraged their long-term implementation. As the 1980s unfolded, many of them were abandoned.

There were several reasons for the failures. Company organizational conflicts were among them. The successful long-term implementation of the philosophy required cooperation between design and manufacturing functions. The problem was that the design or engineering office did not like to be hemmed in by the requirements dictated by manufacturing standardization and vice versa. In most enterprises, these two "fiefdoms" were not anxious to accept one another's dictates.

Cost was another problem. Even when computerized and interactive, the classification of designs and manufacturing processes still required a substantial amount of labor. The potential benefits were significant, but so was the investment. In many cases, the effort was stopped before it started to pay off, because neither engineering nor manufacturing was willing to pay for the staff needed to do the work. In other companies, where the work was started, the costs of classification became an issue when more and more emphasis was placed on cutting all costs down to the bone.

Long-term effectiveness is another issue. When a classification system is used for a considerable amount of time, there tends to be a deterioration in the rigor of employing classification rules. Interactive responses become more casual and less precise as the rules are applied with less and less precision. Errors become commonplace. Parts are incorrectly classified and effective retrieval of optimized methods becomes more difficult.

HOW TO DEVELOP MANUFACTURING GROUPS

As a first step, the development of manufacturing groups requires some measure of parts classification.

There are a number of coding and classification systems that are now in the public domain. A search into these systems, in a technical library, is a good way to start the grouping effort. The lessons to be learned in such a search will include an appreciation of how different coding structures have been organized, what their purposes are, and on what kinds of attributes they are based. For example, some are design retrieval systems and others are structured to be manufacturing coding and classification systems. In this latter category, substantial work was done in the 1940s and 1950s at Germany's University of Aachen by Professor Opitz and others.

As they stand, none of the previously developed systems are likely to meet all of a company's needs. It is better to look at them closely and to take those features that are most applicable to the company's specific needs. For example, the Opitz system was primarily geared to the machine tool industry and has features that can be very useful to a company with many round parts, such as gears.

Armed with an understanding of how coding and classifications work, and of what may be best for the company, it is possible to take the second step: the collection of a random sample of parts.

The Parts Sample

As mentioned earlier, an analysis of a random sample of between 5 and 10 percent of the annual parts production will create a clear picture of the totality of the company's output. It is a good idea to start gradually, with 1 or 2 percent, to avoid being overwhelmed by the task, and to add at a reasonable pace. The random sample should include both manufacturing processes and the drawings that come with the selected parts numbers.

Separation into Parts Families

Using the general layout of a published coding structure as a guide, it now becomes possible to start to separate particular families of parts and to refine the separation as the process goes along. The selection should not be too fine—the company should not have hundreds or thousands of families. It is best to start with no more than 10 or 20 different families.

The first cut for a family formation is made by working with the grouped drawings and related manufacturing plans, based on similarities in how family parts are actually designed and manufactured.

This is not an easy task. Both design and manufacturing engineers have to critically examine the parts within each group and consider what design and manufacturing standards can be applied. Once the initial analysis is complete and the first families have been identified according to their design and manufacturing attributes, a second parts sample needs to be examined. Another 2 or 3 percent of the parts should be evaluated to see if they fall into the families that have already been formed. To accommodate them, it may be necessary to modify the standards on which some or all of the families have been based. It may even be necessary to create additional families. This is not a simple, straightforward process. It is an iterative effort that involves weighing standardization notions against what is possible from a design intent point of view. As it proceeds, some families will be enlarged, and some will be divided into two or three.

Once the second 2 or 3 percent of the parts have been separated into their tentative families, the articulation of the families improves—the definitions of shapes and other design and manufacturing aspects become more refined. This process should then continue, with 3 to 5 percent of the parts at a time, until the groupings of parts within each family starts to stabilize. At some point around 10 percent of annual production, many, but not all, new parts should fit into existing families.

There are two possible reasons for parts not fitting: (1) They may be "oddballs" that are very specific to just one or two products, or (2) they could require a redesign so that they can fit into an existing group. It is important to recognize that it is not likely to be possible to form groups that will contain 100 percent of the parts in a batch manufacturing environment. In the previously mentioned program to standardize the manufacturing of assembly machines for automobile doors, for example, it was possible to fit only about 70 percent of the parts into families. Even in this case, however, it took less than a year to recoup the investment in standardized families.

The Evolution of Standardization

The development of parts families is an evolving process. After families have been defined and parts grouped according to design and/or manufacturing requirements, it may be possible to further refine the families.

For example, it may be possible to form enlarged families so that some parts in the family may go through three operations while other parts may require one or two extra operations. The point is that standardization should not be too restrictive—it is a continuous interaction between manufacturing technology improvement and design requirements.

Once the company has gone through the basic grouping exercise and defined the family parameters, it becomes possible to assign these standardized routings, including the specific operations associated with them, to new parts released from the engineering department. The data for each new part, which may include name, attributes, material, tolerance, and such, is entered into the database. A standard process plan can be immediately generated when the part is released from the engineering department. It may have to be modified slightly, but most of the work is done automatically.

It is not necessary to have a large number of standard process plans—20 or 30 are usually enough for an average manufacturing facility with 15,000 different parts released per year. If the total number of standardized plans is kept to a reasonable minimum, it becomes more likely that they will become very familiar to manufacturing planning engineers. When a part with certain attributes comes from engineering, it is relatively easy to select the standard plan that best fits its attributes.

Capacity Planning

After standardization has been implemented for some time (perhaps three to six months) and the database has been filled up with part numbers, family characteristics, and their standard plans, it becomes possible to take another step: *capacity planning.*

An initial objective is to determine the machine capacity required for manufacturing the parts in a particular family, usually based on such factors as the relationships between frequency of part number releases, family, manufacturing operation details, and lot sizes.

Once this is done, it becomes possible to start setting up cells of machine tools to handle the part families. Here again, it is not realistic to expect that 100 percent of the production will fall in the established families of parts for cellular manufacturing—there will always be some that do not fit. There are several ways to deal with these kinds of parts. One is to establish a general manufacturing cell that can deal with them. Another approach is to take a critical look at these "oddballs" to determine whether they are all necessary. For those that are really needed, the question is whether to make them in-house or to outsource them. In fact, the outsourcing selection can be incorporated into the standardization and capacity management plan.

Flexible Machining Centers

After manufacturing cells have been established for a few different families of parts, the question is whether it makes sense to invest in flexible machining systems for making those families. The data gathered in the standardization and capacity planning efforts can be used to determine the parameters for a flexible manufacturing system for a part family. Again, this is an iterative process.

Organization Issues

There are organizational issues that play a role in achieving success. Leadership is extremely important; chances for success are highest when there is a solid intellectual leader at a higher management level who supports and defends the whole effort. It also appears that dedicating a small group to the program is better than a massive effort. The learning curve is long. It is easier for a small, tightly focused group to learn and succeed than it is for a very large, more diffuse group.

Outsourcing of the analysis is another consideration. An outside consultant might have more experience in dealing with these types of problems and might thus seem very attractive. There is at least one major caveat, however. An outside consultant is not likely to have an insider's knowledge base: the best practices, know-how, and experience. Consequently, the work of any outside consultant needs to be supplemented by a commitment from dedicated insiders who can make sure that the right manufacturing and engineering practices, methods, and standards are employed.

A BRIEF REVIEW

In summary, here are the four basic steps in the development of a group technology or design and manufacturing standardization implementation:

1. Research different classification systems to get a feeling what the classification attributes are and how they can be interpreted vis-à-vis the company's products.
2. Take a step-by-step approach, starting with the analysis of a random selection of perhaps 1 or 2 percent of annual part production to grossly define families. Then increase the size of the sample and use the additional parts to gradually refine the families. After looking at approximately 10 percent of the annual part production, a high degree of design and manufacturing standardization is within reach.
3. Once a significant measure of manufacturing standardization has been achieved, all new parts that are released for manufacturing should be identified by their manufacturing attributes in a relational database by their standard processes and manufacturing attributes, and possibly made using a standard process. This may be the case with 70 percent of the released parts.

4. When the database of newly classified parts becomes large enough, it becomes possible to analyze their manufacturing requirements and estimate the capacity required to make those parts. This can lead to the specification of manufacturing cells and possibly, in the future, flexible manufacturing systems. These manufacturing standardization efforts could also lead to the development of numerical control programs for families of parts, with less effort and fewer errors than would otherwise be possible.

It should be understood that there are no shortcuts in this procedure and that political issues often get in the way of progress. If there is no top management commitment to the effort, its chances of success are very small.

Why Doesn't Everybody Try It?

The road to successful standardization is a difficult path to follow. Long-term strategic thinking and a great deal of effort are required to successfully establish families of parts for design or manufacturing purposes. In many of today's manufacturing environments, the immediate bottom line is often more important than achieving long-term strategic objectives. As a result, while several American companies have implemented successful programs, this approach has gained a bigger foothold in the Far East and Europe than in the United States.

As should be expected, the most enthusiasm has been shown in those environments where the chances of success appear to be the highest. The manufacture of machines that make car subassemblies is an example. It is also promising in many assembly applications, including aircraft assembly. In an aerospace environment, however, design criteria will drive the manufacturing process on many occasions, and manufacturing standardization will not always work back to design standards. And even in the most promising applications, upper management commitment and the willingness of the design and manufacturing people to work together are problem areas.

LOOKING AHEAD

While the progress to date has been uneven, there are new developments to consider. One of them, under consideration by a growing number of companies, is the use of attribute analysis to develop rules for generative manufacturing engineering systems. Design and manufacturing standardization facilitate the development of such rules.

Under any circumstances, the development of the rules requires a substantial effort by highly specialized personnel—knowledge engineers, or artificial intelligence (AI) specialists. Until recently, the return on investment was not high enough to pay for the development of expert-based systems in a general manufacturing environment, especially when very complex parts are involved.

Advances in computer power have made generative planning systems more attractive, but still not always realistic. While it is relatively easy to establish expert rules to make simple shafts or simple gears, making 3-D, 5-axis, sculptured-surface parts is a totally different matter. The rules for making such parts may be too expensive to develop.

On the other hand, current feature-driven, computer-aided design systems may provide the means to translate part attributes into manufacturing requirements. There are signs that this may happen in the future.

Again, it is questionable whether this type of approach will work for complex parts. Furthermore, one should not forget that parts are rarely the final products. Parts manufacturing is usually followed by assembly and, ultimately, final assembly operations. Each may involve different methodologies, quality control, and correction requirements. It is not likely that the universe of parts, subassemblies, and final assemblies will be ruled by expert-based systems in the short-term future.

GROUP TECHNOLOGY

At the same time, even the optimization of small portions of that universe and generation of planning with expert-based systems for those portions might be a worthwhile exercise. Less labor would be needed to prepare manufacturing plans, and with optimized rather than individually developed manufacturing plans, a higher degree of manufacturing automation is possible. A much higher degree of conformance to specifications is also possible, similar to the times when the introduction of numerical control machines substantially enhanced part quality.

At this moment, in the middle of 1998, two things are apparent: On the one hand, there has been a substantial decrease in the classic use of group technology in the manufacturing world; on the other, there may be a growing use of group technology to establish design and manufacturing standards as a base for developing expert-based manufacturing system rules. The general acceptance of feature-driven computer-aided-design systems may greatly enhance the future success of expert-based systems.

There is also some evidence that manufacturing databases can be analyzed by sophisticated computing systems to establish expert rules. These analysis systems try to parse the database relationships between processes and the frequencies of the use of certain processes. Successful analysis could indicate which combinations of manufacturing operations occur most for a given sample of parts. This could lead to manufacturing standardization, without the need for classification. The output might be something like "operation A1 turning, operation A2 fine turning, operation milling, operation hardening, and operation grinding—this sequence happens many times using these and these machine tools." Next it would say, "and by the way, these and these parts have slightly different sequences." It would then be up to the manufacturing and design staff to see whether these parts fall into a particular family.

These programs are very complex and require very substantial computing power because the parsing of the database with all its different variables is a very substantial task. It may be several years before such programs, which are now in development, may be available for general use.

If they become a practical reality, they will dramatically reduce the time-consuming and costly efforts that have discouraged group technology implementations. They may take the theory of group technology full circle from the completely manual classification and analysis systems of the 1930s to much more computerized systems where design attributes are automatically related to manufacturing processes.

However, the emergence of lean manufacturing techniques has brought back many approaches of group technology, albeit under different names: cellular manufacturing, kanban sizing, and so forth. At issue is how this can be rationally integrated with the increasingly popular MRP/ERP philosophy.

BIOGRAPHY

Alexander Houtzeel, founder and president of HMS Software, Inc., was born and raised in the Netherlands. He received his graduate degree in manufacturing from the Delft Institute of Technology and his graduate degree in nuclear engineering from the National Institute of Nuclear Science in Saclay, France. He was employed in the nuclear engineering field in the United States and France for 12 years.

Since 1972, Houtzeel has been heavily involved in computer-aided manufacturing in the United States and has pioneered in the fields of computer-aided group technology and process planning. He has written numerous papers on CAD/CAM.

CHAPTER 17.7

CAD/CAM

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This chapter provides an overview of CAD and CAM technologies. Many industrial engineers use CAD extensively for layout design. For those industrial engineers involved in manufacturing, CAD/CAM is also used for part/product modeling and numerical control part program generation. CAD began as an electronic drafting board, a replacement of the traditional paper and pencil drafting method. Over the years it has evolved into a sophisticated surface and solid modeling tool. Not only can products be represented precisely as a solid, factory shop floors can also be modeled and simulated in 3D. It is an indispensable tool for modern industrial engineers. In this chapter both the fundamentals of CAD and CAM technologies, as well as applications for industrial engineering are discussed

INTRODUCTION

Computer-aided design (CAD) and computer-aided manufacturing (CAM) have drastically transformed the way engineers perform their tasks. CAD and CAM mean different things to different people. The interpretation of the term *CAD* can range from computer-aided drawing and drafting to computer-aided engineering analysis. CAM has been defined by some as the effective utilization of computers in manufacturing, while others consider only computer-assisted numerical control (NC) part programming as CAM. In this chapter we will limit our discussion to computer-aided geometric modeling and computer-assisted part programming.

Many industrial engineers (IEs) use CAD extensively for layout design. For those industrial engineers involved in manufacturing, CAD/CAM is also used for part/product modeling and NC part program generation. CAD began as an electronic drafting board, a replacement of the traditional paper and pencil drafting method. Over the years it has evolved into a sophisticated surface and solid modeling tool. Not only can products be represented precisely as solid models, factory shop floors can also be modeled and simulated in 3D. It is an indispensable tool to modern industrial engineers. In this chapter both the fundamentals of CAD and CAM technologies, as well as applications for industrial engineering are discussed.

Historical Development of CAD and CAM Technology

CAD and CAM are technologies used daily by engineers to model their designs—either a product or a manufacturing system design. CAD has its roots in interactive computer graphics. Before the CAD era, engineering drawings were prepared manually on paper using pencils and drafting instruments on a drafting table. The advent of interactive computer graphics [1] replaced the drafting table with a computer monitor and the pencil with an input device such as a light pen or mouse. Instead of using physical drafting instruments, software commands and icons on the computer display are used. The drawing can be created, modified, copied, and transformed using the software tools. At the time, CAD stood for computer-aided drafting. Drafting was confined to 2D because of the paper limitation. With the computer, such limitation is removed. Three-dimensional CAD systems were developed in the 1960s. In 3D CAD, objects are modeled using 3D coordinates (x, y, and z) instead of 2D coordinates (x and y).* The need for modeling parts and products with complex surfaces motivated the development of free-form surface modelers. Coon's patch, Ferguson's surface, Bezier's surface, B-spline surface, and nonuniform rational B-spline (NURB) surface are a progressive series of free-form curve/surface models developed from the 1960s to the 1980s. Using a surface modeler, complex surfaces can be defined not only by analytical geometry such as cone, sphere, and cylinder but also by free-form surfaces as just described. A complete automobile body can be modeled on a CAD system without needing clay models. Since the surfaces are modeled by mathematical equations, they can be manipulated using geometric transformation such as translation, rotation, scaling, and so on. Colored, shaded images can be displayed on the computer monitor for design visualization and verification. The finished design can also be reproduced into products precisely using computer numerical control (CNC) machines.

The early 3D CAD systems represented engineering objects by their bounding edges. For example, a box is represented by its 12 edges. Each edge is defined by two 3D endpoints. This representation is called a wire-frame representation. Although most of the time a wire-frame representation is sufficient for a human to interpret it, it is ambiguous, in the sense that several interpretations might be possible for a single model. There is also no way to determine the volumetric information about the model. The development of solid modeling in the 1970s is an answer to the need to provide volumetric information in the CAD system. Solid models are geometrically complete and topologically correct mathematical models of 3D objects. Volumetric information and engineering drawings can be derived from the same model. Engineering analysis such as finite element analysis (FEA) can be performed directly on the solid model as well.

The early solid modelers were mostly developed in the university laboratories. Such modelers include BUILD-1 and BUILD-2 [2], PADL-1 and PADL-2 [3,4], GLIDE (system developed by Professor Eastman at CMU), COMPAC (system developed at University of Berlin), TIPS (developed by Professor Okino at University of Hokkaido). Later, many commercial systems and research systems were developed. Although they are powerful in representation, many deficiencies still exist; for example, such systems have extreme computation and resource (memory) requirements (by the standard of the day), an unconventional way of modeling objects, and a lack of tolerancing capability. These early problems slowed the acceptance of solid modeling into the CAD systems. It was not until the mid-1980s that solid modelers made their way into the design environment. By the 1990s, an average desktop personal computer was powerful enough to run the most sophisticated solid model, and the use of solid modelers became commonplace.

The evolution of CAD systems does not stop at this point. In the later part of the 1980s we saw the development of a nonmanifold solid modeler, constrain-based design, variational modeler, parametric modeler, feature-based modeler, and the like. All of them provide either greater flexibility in representing objects (easier model input method) or more consistent models. Technologies developed in these areas have been integrated into many commercial products.

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* Modeling is to prepare a mathematical representation of the engineering object in a computer. A model is such a representation. A modeler is a piece of software that is used by the human to create a model.

So far we have focused on the development of CAD; actually, CAM was developed before CAD. We can trace the origin of CAM to the invention of numerical control (NC). The NC concept is credited to John Parsons. In 1947, Parsons, the president of a Detroit tool company, developed a jig-boring machine controlled by punched cards. In 1949, the U.S. Air Force, encouraged by Parson's success, commissioned the Massachusetts Institute of Technology (MIT) to develop a prototype of a "programmable" milling machine. In 1952, a modified three-axis milling machine was demonstrated and the term *numerical control* was coined [5]. Soon after they started the NC development, the air force realized that it is not easy to program the machine to cut complex geometry. The Automatically Programmed Tool (APT) project thus began. In a broad definition, CAM includes machine control (NC), robotics, a flexible manufacturing system, production scheduling, and so on—applications of computers in manufacturing. However, when linked with CAD, CAM often means NC part programming. In this chapter, we will use the narrow definition of CAM to mean NC part programming. APT, which was first demonstrated in 1956, may be considered the first CAM software. Over the next 20 years, the major development in the CAM area was the improvement of both the geometric coverage and the better algorithms for surface machining. The CAM software can handle not only analytical surfaces but also free-form surfaces. In the 1980s and 1990s even the compound surfaces (surfaces consisting of the intersection or union of multiple surfaces of the same or different types) could be machined automatically by computer-assisted part programming languages. In the 1970s, gradually, CAD and CAM began to integrate. Some CAM packages added front end design to allow interactive part geometry and tool motion command input. Some CAD packages also added part programming languages into their system. Eventually, CAD and CAM integrated. Today, most major design packages are CAD/CAM packages. They have both the CAD and the CAM capabilities built in. These highly graphical packages can also display the simulated NC tool path and machining operations. The finished part geometry can be viewed and visually compared to the design model before the part program is executed on a NC machine.

By the mid-1990s, the drastic performance improvement of personal computers brought enough power to the engineering desktop to allow even the most sophisticated CAD/CAM packages to run on those computers. Also, the availability of large capacity (1 to 10 G byte) yet inexpensive (less than $500) hard drives and the networking capability of desktop computers made it possible for every engineer to have access to CAD/CAM tools and to work with others on collaborative design/manufacturing projects. CAD/CAM is not only a tool for product or process design engineers, it is also a tool used by system designers such as industrial engineers. The 2D templates and 3D-scaled models often used in the past for plant and office layouts have all but disappeared. IEs can even link the 3D computer model with a discrete-event simulator to dynamically simulate the operator of a system in real time.

The popularity of CAD systems also created a new problem: data compatibility. Since each CAD system has its own representation model (data structure to store the design data), it is not possible to transfer data from one CAD system to another directly. A translator must be written to do the data conversion. As the number of CAD systems available on the market increases, the number of translators needed increases exponentially (one translator for each pair of CAD systems). In the early 1980s, an intermediate data exchange format for CAD, Initial Graphics Exchange Standard (IGES), was adopted by the International Organization for Standardization (ISO).* IGES is able to represent 3D analytical geometry, free-form surface, dimensional and tolerance symbols, annotations, and other graphics-related data (line width, style, etc.). Soon after IGES was published in 1980, the CAD community recognized the need to provide data exchange format for the entire product definition data. The new standard is called Product Description Exchange for STEP (PDES).† PDES contains product geometry, product functions, and process plans for the product. The product geometry is expanded to include drawing features, constructive solid geometry (CSG), and boundary representation (B-rep). PDES is also arranged into application areas: mechanical, electrical, AEC, and so on. Since PDES is ambitious in its coverage, the standard is not yet implemented as widely as IGES.

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* For most recent IGES standard, see Ref. [6].

† For most recent PDES standard, see Ref. [7].

As discussed in this section, the CAD and CAM developments have evolved from simple line and circle drawing tools to sophisticated model and manufacturing programming tools. As the functionalities increase, the complexity in using such tools also increases. More effort is being spent in making CAD and CAM tools easier to use.

BASIC MODELING TECHNIQUES

Traditionally, an engineering object was represented using drafting where a typical three-view drawing consisted of projecting the object onto *x-y, y-z,* and *x-z* planes. The projected geometry contains lines, circles, and curves. In order to capture the design's intent, dimensions, dimensional and geometrical tolerances, surface finish, and other notes are placed on the drawing, as well. This additional information is attached to the drawing using lines, circular arcs, and text. A CAD model has to provide at least these types of information: basic geometry and annotation. CAD drafting systems contain exactly the same amount of design information as its paper-based counterpart. However, other CAD methods provide more geometric modeling capabilities. Modern solid models represent the precise volume information for any geometric shapes. There are special tools for assigning dimensions and tolerances to an entity. Many CAD systems automatically insert witness lines and the dimension value to the location specified by the user. Other texts and symbols can also be entered and attached to the geometric entities.

Curves and Curved Surfaces

Basic 3D models can represent only simple geometries such as points, lines, circles, planes, and analytical surfaces. Some curves and surfaces, which are produced by freehand drawing belong to a separate class. In most 2D design systems and graphics packages, free-form curves are available and integrated. Among them, the most popular is Bezier's curve. B-spline curves are also available to some systems. Free-form surfaces, also called *sculptured surfaces,* are usually available in more sophisticated packages. They are usually used for the following applications:

- Die and mold design and manufacturing
- Automobile, ship, and aircraft body design
- Human body model for human factors study
- Commercial and artwork

A free-form surface may be designed directly on a computer using control points, or obtained through surface fitting from a digitized data set. In the first case, an interactive design session allows the designer to sculpture the model by moving control points on the screen. In the latter case, either from an existing object or a clay model sculptured by hand, a scanner digitizes the surface points and feeds them into a math model for surface fitting.

The representation required for curved surfaces and curves is more complex. There are two types of curves: analytical curves and free-form curves. Analytical curves are those that are normally represented by a known equation. The definition of an analytical curve is exact. Free-form curves are those that do not have a known equation. Only a few control points are known.

Bezier's Curve. P. Bezier's at the French automaker Renault invented the Bezier's curve [8]. Since then, it has become the most popular curve design method used in graphics packages and CAD systems. A cubic Bezier's curve is a cubic curve defined by four control points. By moving the control points, the shape of the curve changes. In most CAD systems *rubber banding* is used to help users define the curve.

B-spline Curve. B-spline curves are also very popular since they offer more flexibility than Bezier's curves. In addition to control points, B-spline shapes can also be changed by setting the distances between a series of internal variables. These distances are called *knot span.* A nonuniform B-spline is one that has nonconstant knot span. A cubic B-spline curve can be defined by more than four control points as long as a curve order variable is set to 3.

NURB Curves. To add another level of flexibility, a weight is added to each control point. Such a curve is called a *rational curve.* The nonuniform B-spline with the weights is called a *nonuniform rational B-spline* (NURB). The NURB curve combines features of all the preceding curves. A NURB curve is defined by its control points, knot spacing, and weights. It can be used to fit a complex shape well.

Sculptured Surfaces. A sculptured surface consists of several surface patches (see Fig. 17.7.1). Each surface patch is defined by a set of control points. Surfaces are extensions to the free-form curves and are defined as a *mesh of curves.*

3D Solid Modeling

All the CAD modeling methods discussed so far can produce only drawings. There is no volume information stored in the model. For many applications it is essential that the volume information can be derived from the design model. 3D solid modeling is a solution to this requirement. A 3D solid model not only captures the complete geometry of an object, it also differentiates the inside and the outside of the space occupied by the object in the 3D space. Using this property, the volume of the object and the intersection between two objects can be calculated. Many other volume-related properties can also be obtained from the model. Hidden surface/line removal and image shading can be achieved as well.

When classifying a solid model, its internal representation is usually used. The internal representation is how a computer stores the model. It is different from the external representation, which is how the picture or image is displayed. There are several types of solid internal representation schemes. Among them, constructive solid geometry (CSG) and boundary representation (B-rep) are most commonly used.

Constructive Solid Geometry. Constructive solid geometry is a superior system for creating 3D models. Using primitive shapes as building blocks, CSG employs Boolean set operators ($\cup$ union, – difference, and $\cap$ intersection) to construct an object. A CSG model is represented by a tree structure. At terminals are primitives with dimensions (size of the primitive) and coordinate transforms (location and orientation of the primitive). At the nodes are Boolean operators. CSG models are not unique. The same object may be modeled using different primitives and operation sequences (see Fig. 17.7.2).

Often, a CSG model is converted into a B-rep model. The process is called *boundary evaluation.* Since B-rep has many useful properties, the conversion not only makes the display easier, but also provides other benefits. The user of a CSG system only has to work with the primitives and Boolean operators. The rest are taken care of by the modeler.

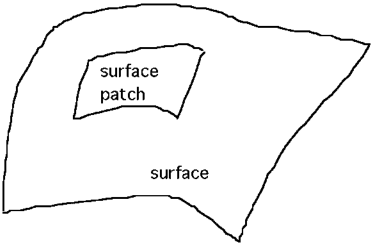

FIGURE 17.7.1 Surface model.

Boundary Representations. Boundary representations (B-rep) are also used to identify an object. In these systems, objects are represented by their bounding faces. For example, in Fig. 17.7.3, the object has 14 faces. Each face contains a set of loops and a face equation. A

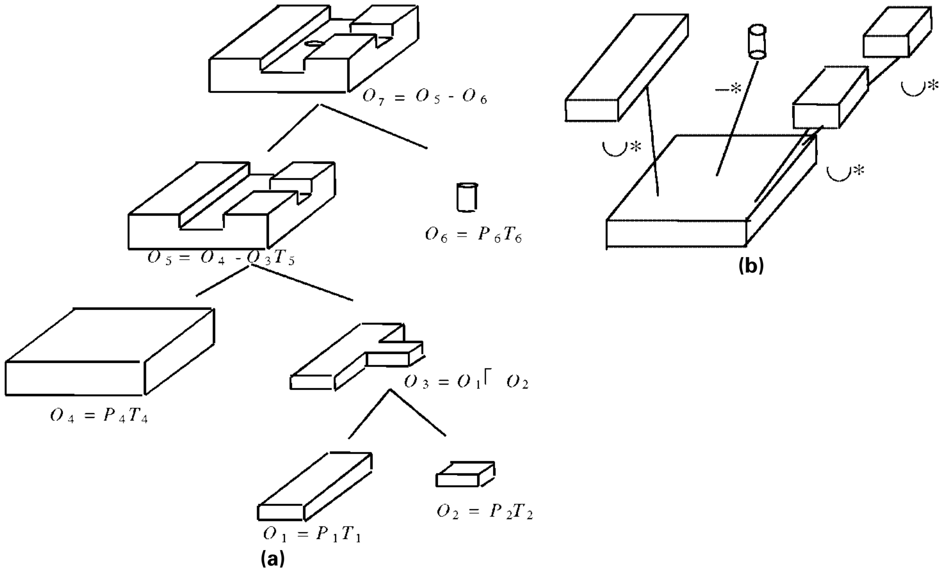

FIGURE 17.7.2 Alternative CSG models of an object. (*a*) a CSG model; (*b*) alternative model.

loop is a closed set of edges. When there are holes or protrusions in a face, additional loops are used to link the edges of the holes or protrusions in the face. Each edge has exactly two vertices. To define the geometry (shape) of the edge, an edge equation (line, circle, curve, etc.) may be included. Finally, a vertex is defined by its x, y, and z coordinates. A set of operators called *Euler operators* are available to build a B-rep from the ground up. To build a B-rep model by hand is very tedious. Most B-rep models are derived from a CSG model through boundary evaluation.

Manifold and Nonmanifold Models. Currently the majority of 3D solid modelers are based on either CSG or B-rep representations. CSG data input is the most popular. Often many face types can be used in the solid model. The 3D solid models discussed so far are called *manifold* models (2-manifold). In a 3D manifold model, the dimensionality is maintained. The B-rep of an object consists only of bounded faces with no loose edge or face. Each edge is bounded by exactly two vertices and adjacent to exactly two faces. Each vertex belongs to one disk (traveling from one adjacent face to another and will never cross the vertex itself). The manifold model does not allow any dangling faces and edges. However, there are also *non manifold* modelers. A nonmanifold model allows additional faces and edges to exist in a solid model. To track the inside and outside becomes more complex. However, a nonmanifold modeler such as ACIS (it is used in many CAD systems including AutoCAD R13) allows much more flexibility. More design intents can be saved in the design model.

Since solid model representation is complete, engineering analysis can be performed directly with the model. It also provides a common linkage between design, analysis, and manufacturing. For applications such as rapid prototyping (layered manufacturing), a solid model is a must. A machine like a stereolithography device takes as input a 3D solid model in a special B-rep format called an STL file (it is a triangulated B-rep model). The machine-control computer slices the model into thin layers. A laser beam is used to draw the cross section of the layers and selectively cure the photopolymer. Parts can be built directly from the solid model representation.

Design with Solid. Design using a solid is quite different than design using other models. To build a solid object one uses solid primitives and Boolean operators (union, difference, and intersection). Often, solid primitives can be built using sweeping operators, either linear

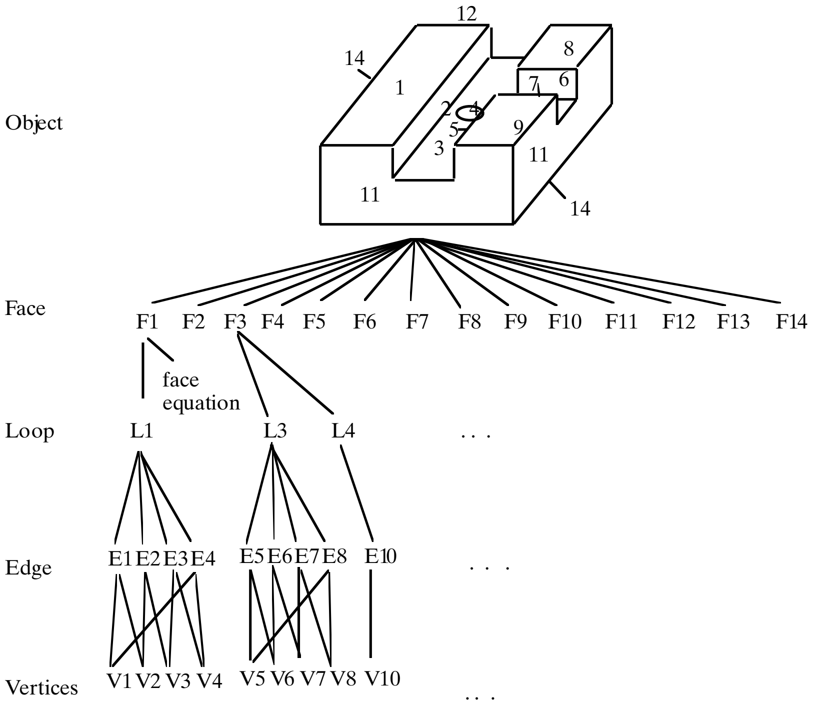
Object
12
14
8
1
7
6
2
4
5
9
3
11
11
14
Face
F1 F2 F3 F4 F5 F6 F7 F8 F9 F10 F11 F12 F13 F14
face equation
Loop
L1 L3 L4 . . .
Edge
E1 E2 E3 E4 E5 E6 E7 E8 E10 . . .
Vertices
V1 V2 V3 V4 V5 V6 V7 V8 V10 . . .

FIGURE 17.7.3 B-rep model.

sweep (extrude) or rotational sweep (revolve). To extrude a primitive, one first defines a 2D polygon and then extrudes it through a path. This path can be at a right angle with the 2D polygon or at any other angle. Some CAD systems also allow this path to be a curve. Revolve is done by defining a 2D shape and an axis of revolution.

To build a solid object, primitives must first be defined. Each primitive has a set of attributes such as the length, width, or height of a box, or the radius of a sphere. The primitives may be rotated and moved (translated) before they are joined (union) together or subtracted (difference) from one another. Graphics tools are available to precisely align the faces or edges of one primitive against another. During the design process, the solid is usually displayed as wireframe. Rendering tools are used to add color, lighting, and surface texture onto the object. Since rendering is slow and the rendered image lacks well-defined edges, the design is done using the wire-frame drawing.

Feature-Based Modeling

The data available in geometric models is at a low level: faces, edges, vertices, and the like, or solid primitives in a CSG model along with set operations. The data is often not directly suitable for performing analysis for downstream applications such as design for manufacturability analysis, process planning, and so on. Entities are needed for reasoning about the part; these applications are not explicitly available in these models, and extraction of these is a nontrivial task.

The next step in the evolution of CAD systems and product modeling techniques aimed at pushing the geometric models into product models introduced features that can be used in various stages of the product life cycle. In feature-based modelers, parts are viewed as a set of features that can best be described as a higher level entity imparting engineering significance to the geometry of the part or assembly. A feature-based model can be viewed as consisting of two interrelated components: the feature model and an associated geometric model (Fig. 17.7.4). Several different approaches have been taken to create the feature models.

Interactive Feature Definition. A typical geometric model is created in the traditional manner, and features of interest are later defined interactively by picking the elements of the geometry and topological entities that correspond to a feature. This approach is not very popular for design purposes, but provides a means for creating a feature library interactively, and for creating user-defined features.

Automatic Feature Recognition. In this approach, the geometric model is also created first, and computer programs are used to automatically recognize part features from the underlying geometry and topology of the part model. Algorithms capable of automatic feature recognition are based on recognizing machining volumes, and recognizing predefined features from the part geometry and topology. Automatic feature extraction still lacks robust recognition algorithms, have difficulty in recognition of features in the presence of feature interactions, and are often limited to classes of predefined features.

Design by Features. The part is created by the addition of features, and each feature changes the part geometry and adds information to the part model. Feature definitions are provided in libraries from which features to be used are instantiated by specifying the various parameters needed to completely specify the feature. The parameters may include dimensions, location parameters, constraints, and relationships. The manner in which the constraints are handled is different in different systems, and a further distinction can be made to partition the design by features approach into parametric and variational systems.

Since design by features is the most popular approach, we will focus our discussion on other aspects of these systems.

Features are often related to the process used to design, manufacture, or inspect parts, and are often specific to the application. There are various types of features that can be used for modeling.

Geometric form features—geometric shapes that occur frequently in parts

Tolerance features—features related to the specification of tolerances, such as datums

Manufacturing features—features derived based on the manufacturing process used: hole, shaft, chamfer, slot, round, cut, protrusion, flange, rib, shell

Design construction features—features used to enable construction of the part, for example, datum planes, coordinate systems, and axis

Assembly features—features describing relationships of various parts in an assembly, such as mating conditions, relative positions, fits, kinematics relations

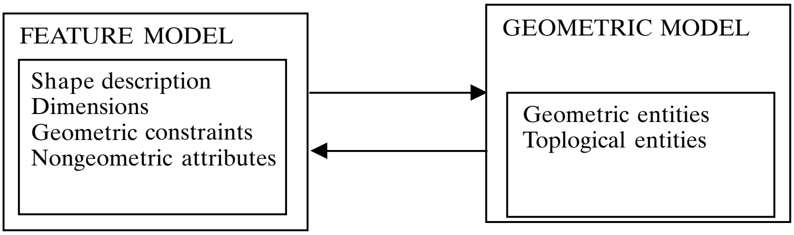

FIGURE 17.7.4 Feature model and the associated geometric model.

The different features cannot all be defined a priori. Most modelers will provide a diverse set of features to support the application domains supported by the modeler. Most modelers also provide the capability of including user-defined features, and support the creation of a user-defined feature library to customize the features for the user's particular domain.

Parts are stored as a series of features. Underlying each feature is the geometric information associated with the feature. The shape of the feature is defined by the dimensions and its geometric and topological entities, and by its relationship to other features. Figure 17.7.5 shows a part that is constructed using features. Initially the design construction features—datum planes and coordinates systems—are defined, then the first feature is created as an extrusion, followed by a cut feature, and a hole feature. The relationships between the features are defined through the dimensioning scheme used to place the various features with respect to each other. Further defining relations between the various parameters captures the design intent. For example, if the designer's intent is to maintain the hole in the center of the block, then relations defining the parameters used for the hole placement are used to enforce this design intent. This imposes a hierarchical ordering among the features, which is often represented in the form of parent-child relationships. Since the model is created using one feature at a time, the creation of these parent-child relationships often has an impact on editing of the features and feature deletion. For example, in Fig. 17.7.5, the hole feature is a child of the slot feature since it is dimensioned from the edge of the slot. Deleting the slot feature will have an impact on the hole feature.

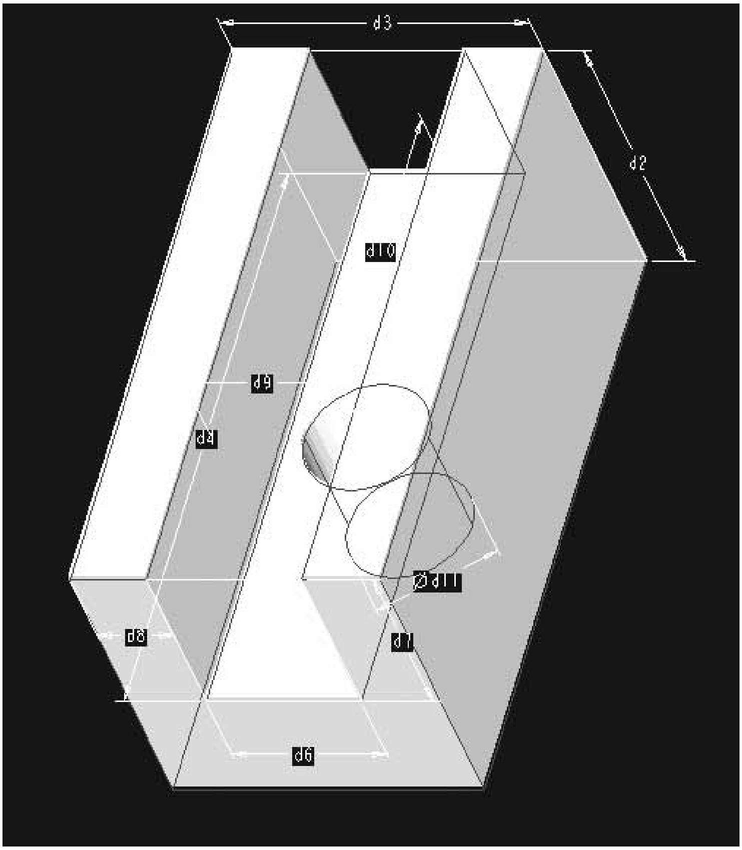

FIGURE 17.7.5 Part construction using features.

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CAD/CAM

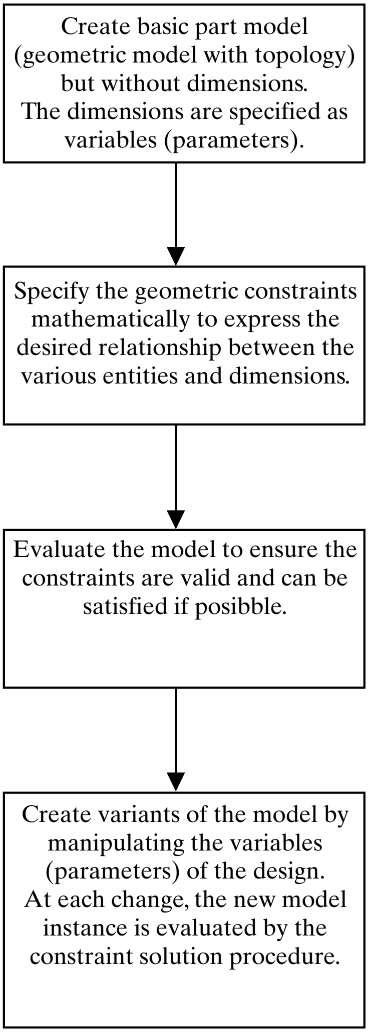

Create basic part model
(geometric model with topology)
but without dimensions.
The dimensions are specified as
variables (parameters).
Specify the geometric constraints
mathematically to express the
desired relationship between the
various entities and dimensions.
Evaluate the model to ensure the
constraints are valid and can be
satisfied if posibble.
Create variants of the model by
manipulating the variables
(parameters) of the design.
At each change, the new model
instance is evaluated by the
constraint solution procedure.

FIGURE 17.7.6 Design process using variational/parametric modeler.

Variational and Parametric Modeling

The other problem associated with using only geometric models is the lack of ability to capture design intent. For example, if the designer requires that a hole be centered in a block, then in a pure geometric model, the hole would be designed using a cylinder primitive and a Boolean subtraction operation, and be placed in the center of the block. If subsequently the designer changed the dimensions of the block, the hole would no longer be centered.

This problem can be addressed by specifying the model in terms of various constraints between the higher level entities or features used to design the part. Instead of specifying rigid dimensions, the model can be specified in terms of the geometric constraints between the entities. In the example, instead of explicitly specifying the dimensions of the hole from each face, we can specify the dimension as a constraint (or relationship) based on the size of the block. The hole is located at a distance $d9 = d3/2$ and $d10 = d4/2$ from the two edges of the part, where d3 and d4 are the dimensions of the block. In this case, the dimensions locating the hole are specified as relations based on the block dimensions. Now if the designer changes the size of the block, the hole will still remain centered in the block.

Since the parts dimensions have specific variables associated with them called parameters, and making changes to the parameters and subsequent reevaluation of the constraints and relations can easily create new parts, these approaches are called *parametric or variational models*. The terms *parametric* and *variational* are often used interchangeably in the commercial CAD community. Although fundamental technical differences exist, they support similar design process and to the end user the two types of systems are similar.

Variational/parametric modelers were developed to address two main design concerns: (1) the inability of geometric modelers to capture design intent, and (2) to support the concept of variational design. Eighty percent of all design tasks are adaptations and modifications of existing designs, and often reuse of existing drawings with small changes are important to support standardized parts and product families. The flowchart shown in Fig. 17.7.6 illustrates the design process using a variational/parametric modeler.

The basic technical difference between the parametric and variational approach is the way in which the constraints are defined and solved. In the parametric approach, the construction is modeled as a sequence of assignments to model variables, where each assignment computes the values of model variables as a function of previously computed variables or original parameters. Hence this approach dictates a sequential strategy for evaluating the constraint equations. To create variations of the product, the parameters are changed and the design construction sequence is reevaluated to create the part. Variational systems, on the other hand, employ simultaneous solutions to the set of governing equations representing the constraints.

Parametric models can be evaluated quickly since they don't require solving complex simultaneous solutions of equations, and equations are solved one at a time in a sequential manner. However, they cannot deal with constraints that are mutually coupled. Variational models can handle mutually coupled constraints but are much slower and limited in their capability to handle models that have inconsistencies and are incompletely satisfied.

APPLICATIONS OF CAD FOR IE

Facilities Layout

CAD systems are finding increasing use in the facilities layout domain. These systems allow the users to create a graphical layout in 2 or 3D interactively with a CAD system using features and symbols from libraries unique to industrial facilities such as cranes, racks, conveyors, and machine tools. In addition to the layout creation tools, these software programs also provide a wide range of analysis tools to help the user evaluate the layout in terms of material flow, distance traveled, and so on. The layout planner uses the CAD and interactive computer graphics to modify the layout, and the programs provide the graphical and numerical analysis of the changes in the performance measures. This approach provides a computerized implementation of manual process where the power of the computer is used to provide the CAD tools for layout creation and layout analysis, while all decisions are made by the planner.

Data required by CAD-based layout programs encompass actual facilities drawings as a CAD model, material flow paths with production and material-handling data, product routings, production volumes, costs of material handling, and so forth. The amount of information needed depends on the detail required in the analysis and in the ability of the software to perform the various analyses. The outputs could include graphical and numerical comparisons for alternative layouts, different levels of production, alternate production routings, or different material-handling methods. The measure of comparison may include total move distances, move intensities, move costs, and material-handling equipment utilization, to name a few.

The advantage of CAD-based layout methods is that they allow the planner to focus on what humans do best, while the computer performs the numerical computations and graphical displays to help evaluate the results. This approach depends on the creativity of the planner to generate useful alternatives, because these programs often do not attempt to optimize or change the layout. Layout planning can be performed at several levels of detail and abstraction, and it is the users' responsibility to select the right level of detail for the task. For example, if a new facility is being planned, it can be expected that it would undergo several changes, and creating a detailed layout with all machines, racks, aisles, and the like would require having to rearrange a large number of components. In this case it might be best to start with a block layout and rough aggregate data, followed by a detailed layout of the individual areas.

One example of CAD-assisted factory layout software is FACTORY suite, consisting of Factory Plan, Factory CAD, and Factory-Flow (EAI corporation). Factory CAD is the basic layout drawing tool and it integrates with AutoCAD to provide a complete graphic library for drawing, planning, and managing industrial facilities. Factory CAD tools allow easy placement of drawing grids, walls, windows, utility lines, machine symbols, conveyors, cranes, and more. Factory Plan provides a means for analyzing the initial layout phase of a facilities design project. It is intended for a qualitative analysis and evaluation of multiple alternatives, using the systematic layout planning (SLP) techniques. Before proceeding with a detailed layout planning and analysis, Factory Plan can be used at an aggregate level. Flow-related data or an aggregate of closeness desired and flow data is used for the basis of scoring and visual diagramming.

Factory-Flow integrates the AutoCAD facility design with material-handling data, product routing, and production volume data. The travel distances are obtained automatically from CAD layouts. The program then overlays colored lines indicating material flow intensity between departments or machines, and provides a graphical view of the product flow diagrams. Various reports, such as material-handling distance traveled and cost by product types and between pairs of departments, can be easily generated. Advanced features include congestion analysis, distance intensity, and from-to charting, among others. Figure 17.7.7 shows a before and after view of a facility layout during the analysis stages.

The planner identifies the problem areas, creates alternative solutions, and the program repeats the calculations providing data and comparison between the different scenarios. The planner can perform what-if analysis by allowing the user to vary the inputs.

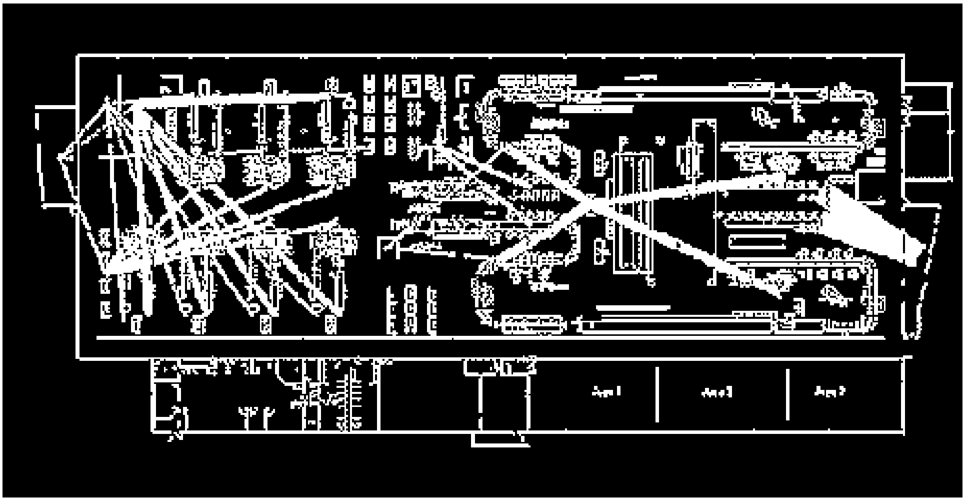


FIGURE 17.7.7 Facility layout with CAD.

Human Factors Model (Human Model)

The use of digital humans in simulations is an area of growing interest, and can be traced to two major factors. First, the advances in computer graphics and modeling technology have provided the speed and performance necessary to efficiently duplicate and visualize human motion. Second, there is an increasing awareness of the role of ergonomics in the design cycle. Given that most product modeling is done in the virtual space using CAD models, it is easy to visualize a CAD-based human being used to test the fit, view, and accessibility in the CAD models. The goal is to verify the design against variable anthropometry of the target operator population, to analyze spatial accommodation, posture, reaching abilities, clearance and interference of body segments, field of vision, biomechanical stress, and other work-related issues.

Almost all aerospace and automotive manufacturers are using some aspect of digital human modeling to support product design and development. A digital manufacturing environment complete with human models interacting with the existing CAD and layout data is desirable to avoid the time and expense of building physical mock-ups of processes and tasks. Human simulations provide graphics demonstrations of operator interaction with products and processes and analysis of the operator's productivity and physical capabilities. The current trend is to integrate the 3D human simulations with typical industrial engineering applications—integration with labor standards will assist in the development of cycle time. A package integrated with assembly sequencing capabilities will help address build and quality issues. Most available human modeling systems have standard ergonomic assessment functions such as reach, posture, lifting, and operator vision in every analysis. Another role for digital humans integrated into CAD environments is the creation of a virtual environment to support design and manufacturing.

BOEMAN was one of the first human modeling programs used by Boeing in the early 1960s to assess the fit of the operator to the airplane cockpit. Over the years, several human modeling programs have been developed to exploit the improvements in computer technology. Examples of such software include CYBERMAN, COMBIMAN, CREW, CHEILF, JACK, SAMMIE, MANEQUINN, and MQPro [9,10].

MQPro is an example of a personal computer (PC) based program for computer-aided ergonomic design. Users can quickly construct 3D models of human or skeletal figures, or choose figures from any of 11 populations in the database. The database includes adults and children of both sexes and physically challenged human models. The figures have motion within the full normal range and can be animated one frame at a time, or walked along a path. The software allows the user to "see" what the figure would see. Applying forces and torque in various directions on individual body parts simulates pulling, pushing, and lifting forces. A series of tasks and movements can be three-dimensionally constructed and evaluated before implementation. For engineers, architects, and ergonomics and safety professionals, this kind of CAD application allows building the human factors into the task and workplace as they are being designed.

Transom Jack is another example of a 3D human simulation system. It provides a human model with 74 sections, 73 joints, a 22-segment spine, and 150 degrees of freedom derived from the anthropometric data. Figure 17.7.8 shows a sample output from Transom Jack.

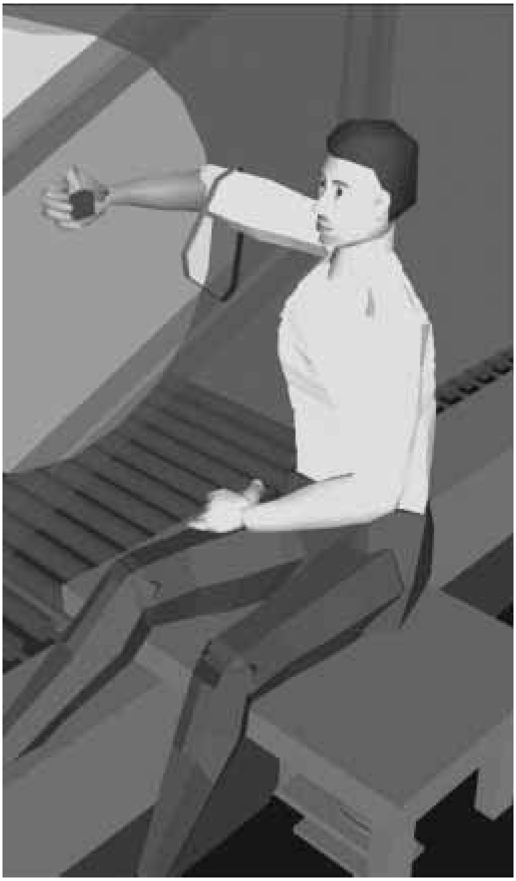


FIGURE 17.7.8 Human model.

CAM

As mentioned in the introduction, we will limit our definition of CAM to NC part programming. However, since rapid prototyping is becoming a popular manufacturing alternative, we will include a discussion on solid modeling for rapid prototyping.

NC Tool Path Generation

One of the earliest CAM applications is NC tool path generation—computer-assisted part programming language. As soon as the NC machine was invented, it was realized that programming such a machine manually would be too tedious. One must calculate the tool center offset. Trigonometry is used to calculate the offset. Even for simple geometry, the calculation is quite tedious. For cutting a curve or designing a curved surface, the calculation is too complex to do manually. In addition to the tool offset, the curve or curved surfaces are approximated using line segment. The approximation error also needs to be taken into consideration. The approximation error must be less than a manufacturing tolerance. For any surface and volume to be removed, multiple passes are needed to clear the enclosed area. During the tool path computation, one also needs to prevent overcut of the surface by another part of the tool. To complicate the matter further, the noncutting part of a tool may clash with the workpiece and must be prevented.

The Automatically Programmed Tool language [11] was developed to solve complex, tedious calculations. APT is a high-level part programming language. The major sections of APT include geometry definitions and tool motion statements. APT provided a set of geometry definition methods similar to those used in the 3D CAD system. After the geometry has been defined, a programmer can program the tool motion by issuing commands such as “go/to, line1,” “golft/line1, past,circle2,” and so forth. The tool offset and curve approximation are calculated automatically by APT. The output of the APT language processor is a data file called CLDATA. CLDATA contains the cutter location data and other machine control information. Since each NC machine uses a different part program format, a software program called postprocessor is written for each NC machine. This postprocessor is used to translate the neutral data file CLDATA into the machine-specific part program in N-G code. Many computer-assisted part programming languages have been developed and used over the past four decades. The geometric definition methods in APT are integrated into the CAD systems.

Since a CAD model contains the part geometry, it is natural to add tool motion statements into the CAD system. With the addition of tool motion statements, the CAD system is able to generate tool path directly from the design model. Hence the term *CAD/CAM* was created. A CAD/CAM system uses the CAD geometry for tool path generation. Many of the basic geometric calculation functions needed by part programming are also available in the CAD package. This marriage produces a powerful tool that not only integrates two applications but also allows the output of the CAM part program to be graphically simulated/verified using the CAD graphics functions. It makes the part programming task much easier. The generated tool path is displayed over the part geometry. The finished tool path is post processed into the machine-specific N-G codes.

Many CAM packages also have built-in communication functions. The post processed tool path can be downloaded (sent) to a machine tool through a serial communication port (such as RS 232 port). Some sophisticated CAM packages can generate tool paths not only for simple 2½ D geometry and pockets, but also for compounded NURB surfaces.

Rapid Prototyping

Rapid prototyping is a new class of processes that were invented in the late 1980s and became commercially available in the 1990s [12,13]. Also, *rapid prototyping* refers to any manufacturing processes that can create a prototype part quickly. The process can be manual, NC, or using any other method. However, the term *rapid prototyping* in recent years has been borrowed to describe the new class of processes that use layer-by-layer construction of a 3D object directly from a solid model. It is also been called 3D fabrication, desktop manufacturing, automated fabrication, tool-less manufacturing, free-form fabrication, and layered manufacturing. It is made possible only with the solid modeling design tool. Therefore, it is appropriate to include it in this CAM section.

The first rapid prototyping process was developed and marketed by 3D Systems. The process is called stereolithography (3D printing in Latin) The machine is called a StereoLithography Apparatus (SLA). It selectively cures photopolymers using an ultraviolet (UV) laser. The designed object in a 3D solid model is sliced by the computer to generate 2D boundaries. The enclosed 2D area is drawn by the laser, thus curing the polymer. Layer by layer the polymer is cured to form a 3D object. The layer is usually very thin. The process may take several hours to complete. However, the complexity of the object is no longer an issue in manufacturing. The machine is totally automatic.

The model used by a SLA machine is a tessellated triangular facet model. It is an approximation of the original model. The reason for using such an approximation is to simplify the slicing operation. It is much faster for the computer to slice a triangular facet model since all faces are triangular faces. The slicing is done by intersecting a plane defined by z = constant with all the faces in the part. This triangulation does introduce error in the part. Each facet is represented in a format shown in Fig. 17.7.9. It simply consists of coordinates of three vertices of the triangular face and a face normal vector.

```
solid    name
         facet  normal    ni  nj  nk
                         outer  loop
                   vertex  v1x  v1y  v1z
                   vertex  v2x  v2y  v2z
                   vertex  v3x  v3y  v3z
                   endloop
         endfacet
endsolid   name
```

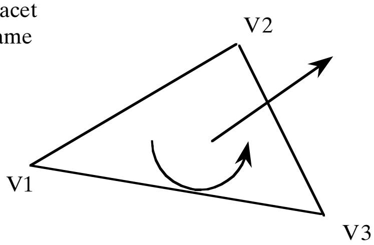


FIGURE 17.7.9 A triangular facet using an STL model.

Parts built using the stereolithography process are usually plastic. To make metal parts, the plastic part is used as the pattern. Since the part (pattern) can be made directly from the 3D solid model of the design, the art-to-part time is drastically reduced. Many other processes have been developed since the early 1990s. All of them used the basic principle of slicing the solid model into layers and built the part layer by layer. The selective laser sintering process uses a powerful laser to fuse wax or plastic powder on a layer. The fused deposition modeling process uses an injection head to inject either molten wax or molten plastic. The laminated object manufacturing machine uses a laser to cut paper with back glue. Layers of papers are glued together to form the part. The 3D printing process uses a inkjet printer head to drop binding agent onto a layer of powder. The green part (powder) is sintered into a solid. There are some other processes either derived from the aforementioned processes or using other layered additive processes. As material property and process accuracy improve, the prototype parts can be used for not only geometric checking but also functional testing.

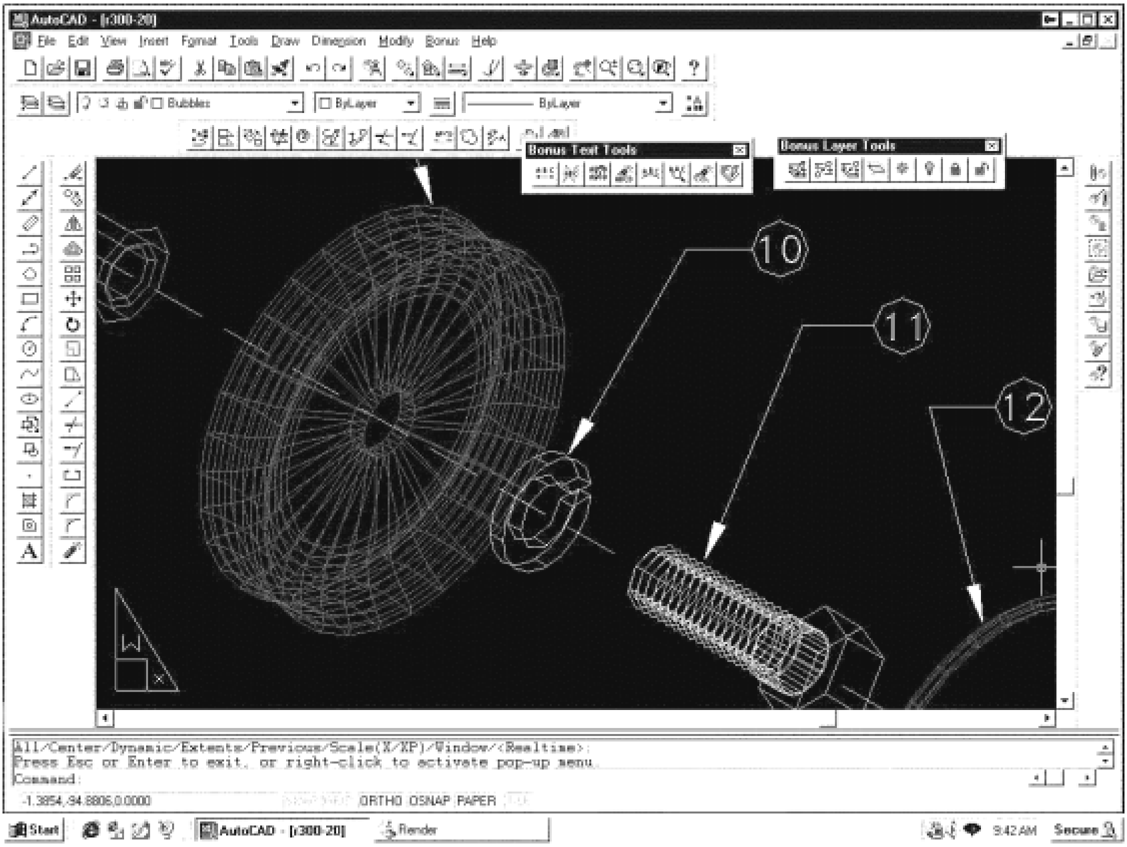
EXAMPLE CAD AND CAM SYSTEMS

AutoCAD

AutoCAD is one of the most successful CAD packages in the late 1980s and 1990s. It began as a PC-based drafting package running under the MS-DOS environment. However, it gradually evolved into a full-blown CAD system. It supports nearly all the advanced functions found in more expensive packages and runs on most computer platforms. However, AutoCAD is still a single-user design package (only one user can work on the same design data file at a time). AutoCAD supports a standard file exchange format—DXF, and an interface language—AutoLisp. Many add-on applications have been written for AutoCAD. Special applications can use application-specific interfaces and the underlying AutoCAD geometry and functions. Through DXF the design data file can also be transferred into other applications including NC tool path generation packages for part programming.

The most basic functions of AutoCAD are the 2D drafting functions. 2D geometry such as line, circles, and curves can be defined. A 2D profile can also be extruded into a 2½ D object. The extruded object is a wireframe of the object. AutoCAD also allows a 3D wire-frame to be defined. To cover the wire-frame model, faces can be added to the model. This creates a shell of the object. Hidden line/surface algorithms can be applied to create realistic pictures. Many menu functions are used to help simplify the design process. Annotation and dimensioning are also supported. Text and dimension symbols can be placed anywhere on the drawing, at any angle, and at any size. A sample drawing is shown in Fig. 17.7.10.

A screen menu or a tablet menu helps the user select the right command. The menus are user configurable. The user can also define symbols (shapes) using lines, arcs, and circles, and save them in files. Shapes can be loaded in and used in a drawing.



```
All/Center/Dynamic/Extents/Previous/Scale(X/XP)/Window/<Realtime>:
Press Esc or Enter to exit, or right-click to activate pop-up menu.
Command:
```

-1.3854,94.8806,0.0000 ORTHO OSNAP PAPER

FIGURE 17.7.10 AutoCAD example. *(Courtesy of AutoDesk, Inc.)*

In addition to the drafting functions, AutoCAD also includes a true 3D solid modeling capability. Since release 13, the internal solid modeler is ACIS, a nonmanifold solid modeler. The 3D solids created by AutoCAD are integrated into the overall design data. A CSG-based user interface is available to the user. 3D primitives used in the design include BOX, WEDGE, CYLINDER, CONE, SPHERE, and TORUS. Primitives can also be created from 2D entities using EXTRUDE (translation sweep) and REVOLVE (rotation sweep) commands. Boolean operators, UNION, SUBTRACT, and INTERFERE are used to construct solids from primitives. Other commands such as CHAMFER (chamfering), FILLET (fillet a corner), and SLICE (slice an object in two) modify the model. The surface area can be calculated using the AREA command. The mass property including mass, volume, bounding box, centroid, moments of inertia, products of inertia, radii of gyration, and principle moments are calculated using the MASSPROP command. Given two solids, the INTERFERE command can find the portion of the solids that overlap in the space. The resultant solid can be displayed as a 2D drawing (projection), 3D wire-frame, or shaded image. An application program called AutoVision can use surface texture mapping or lighting design to create realistic images of objects such as a machine, an office, a building, or a landscape. It performs both rendering of a picture and animation of a sequence of motions through a model.

MasterCAM

MasterCAM is a PC-based, mechanical CAD/CAM system. MasterCAM provides full 2D and 3D design capability for drawing mechanical parts, and creates output code for programming computer numerical control (CNC) mills, lasers, plasma cutting tools, lathes, wire EDMs, and other machine tools.

The CAD portion of the software includes 2D and 3D wire-frame and surface modeling capabilities. It provides a range of tools for drawing parts and editing geometry and is capable of modeling 2D profiles, as well as creating 3D multisurface models. Although not as powerful in its capabilities when compared with high-end CAD packages, it provides a basic range of tools to enable creation of mechanical parts. Built-in bidirectional translators include IGES, DXF, and STL to allow integration with other CAD systems and provide the capability of importing CAD models made using other CAD systems.

Once a part is entered into MasterCAM (either by creating it using the CAD portion of the software or by importing from another CAD system), the user then interactively specifies the contour, pockets, or surfaces to be machined by selecting the appropriate geometry. Next the user specifies the manner in which the feature is to be cut. For example, for a pocket feature, the user can specify pocketing styles (zigzag, spiral, one-way, etc.), choose the type of entry into the pocket (helical, ramp, etc.), and make other pocket machining choices. In addition to specifying the machining/cutting parameters, the user also needs to specify NC-related parameters. Examples of these parameters include tool size, cutting speed, feed rate, coolant on/off, cutter offset methods, and postprocessor information.

The program then automatically computes the cutter path based on the information supplied by the user. The cutter path is displayed on the screen to provide visual feedback and to help in interactively modifying the tool path if necessary. In addition to providing tool path generation, MasterCAM provides a solid-based tool path verification that allows the user to watch the part being cut from a solid block of material. Both the tool and the toolholder are checked and displayed during simulation. MasterCAM also offers other features for debugging, such as the ability to step through the program with the tool path back-plotting function, and provides an estimation of the cutting time.

Another advantage of MasterCAM is the capability to store a library of commonly used operations to automate machining. For example, one can spot drill, peck drill, and tap a series of holes simply by importing one stored operation sequence from the library. User-customizable tool and material libraries are also included to automatically calculate feeds and speeds for cutting. Associative tool paths, which are geared toward increasing productivity and managing design and corresponding NC-program changes, are another feature. Thus the tool paths generated are linked to the geometry, and when the geometry is updated, the tool path is automatically updated without explicitly conducting the interactive procedure used to generate the initial tool path. This feature makes it easier to propagate design changes to the NC programs.

To increase the flexibility and incorporate custom programming for specialized applications, MasterCAM also provides a C language interface. Several customized programs that hook into MasterCAM are also available through third-party vendors, thus enhancing the scope of the software. A sample MasterCAM tool path is shown in Fig. 17.7.11.

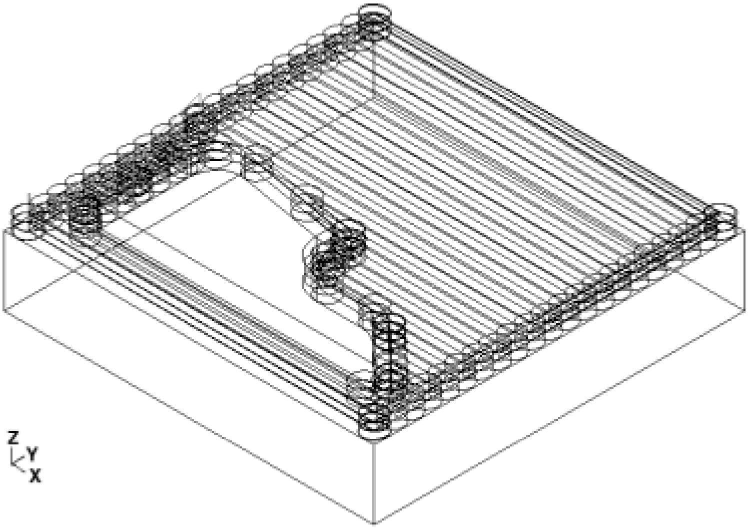


FIGURE 17.7.11 Display of a tool path generated by MasterCAM. *(Courtesy of CNC Software.)*

Pro/ENGINEER

Pro/ENGINEER from Parametric Technology Corporation is a fully integrated design-through-manufacturing solution based on a single associative database that provides tools to allow product development and manufacturing companies to modernize their product design process and greatly reduce their time-to-market. The Pro/ENGINEER design solution consists of a feature-based, parametric modeler with full associativity that allows the user to work simultaneously with solids, surfaces, and wire-frame methods. Its parametric solid modeling methodologies capture design intent and support feature-based modeling of parts and the subsequent combination of parts in assembly creation.

The feature-based capabilities of Pro/ENGINEER allow users to create the various parts that determine the product by specifying features like holes, rounds, ribs, and slots that have some engineering significance, rather than specifying geometry using geometric entities such as lines, arcs, planes, and surfaces. *Parametric* means that the feature dimensions drive the shape of a part. A user can define, or redefine, a feature's dimensions at any stage in the product design process, and as a result, radically change the shape of a part by redefining the values of its dimensions. These parametric capabilities of Pro/ENGINEER mean that if a shape, or design is created, the model can be changed simply by selecting a dimension, keying in a new value, and asking the system to update the geometry.

The fully associativity of the Pro/ENGINEER family of products allows users to capture accurate product and process information and make that information available to engineering users throughout the entire company. Product development teams using Pro/ENGINEER can benefit greatly from its bidirectional associativity, due to its single database, since changes can be made at any time to any Pro/ENGINEER object (part, drawing, assembly, or manufacturing model) and are automatically reflected in all engineering deliverables. Full associativity means that engineers can work concurrently on part design, assembly design, and product manufacturing and have their work automatically propagated throughout.

The Pro/ENGINEER modeler maintains a complete, accurate, and unambiguous 3D-boundary representation of the feature-based solid model. This means that a user can treat the model as though it is a solid, and use it for virtual prototyping. Pro/ENGINEER contains tools for the design and management of large product assemblies, including the ability to create families of assemblies, exchange subcomponents for design variation, use various visualization tools, and so on. It supports both the top-down and bottom-up product development paradigms. Pro/ENGINEER also contains tools for creation of downstream deliverables such as engineering drawings, bill of materials, and completely parametric CNC tool paths. The parametric and fully associative nature of Pro/ENGINEER allows reuse of engineering data for subsequent engineering design. The designers can embed their design knowledge and intent into the solid models and reuse these models for future designs by parametrically changing their shapes and sizes. This provides a potential for gains in productivity, vastly reducing time-to-market, and minimizing expensive design modifications due to design incompatibilities with downstream processes.

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BIOGRAPHIES

Tien-Chien Chang, Ph.D., is a professor of industrial engineering at Purdue University. He earned a B.S. degree in industrial engineering with a minor in mechanical engineering from Chung Yuan University, Taiwan, and M.S. and Ph.D. degrees in industrial engineering from Virginia Tech. Chang is an author and coauthor of five books and more than 100 technical papers in journals and conferences.

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CHAPTER 17.8

ASSEMBLY LINE BALANCING

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We may not know it, but assembly lines have had a major impact on our everyday lives—by lowering costs and making products more affordable. We wear, use, breathe, and drive products made in assembly lines. Assembly lines were first made popular by Henry Ford, making the now famous Model-T Ford automobile affordable to the general population. Since then, assembly lines have been utilized to manufacture a wide variety of goods, ranging from small watches to large boats. This chapter will discuss the definition of assembly lines, methods of assembly line balancing, software, and other related advanced features.

WHAT ARE ASSEMBLY LINES?

Assembly lines can be defined as a series of manual or automated assembly workstations through which one or multiple product(s) are sequentially assembled. A broader definition of assembly lines includes flow lines, with or without buffers between workstations for manufacturing and assembly. Assembly lines form the backbone of mass production methodologies and are the basis for a *product flow* layout. For assembly line analyses, and to realize the efficiencies of mass production, we assume that the line is *synchronous* [i.e., partially assembled products within the assembly line leave each workstation synchronously (or at the same time)].

MODELING AN ASSEMBLY LINE

Manufacturing and assembly tasks can usually be decomposed into work elements. A *work element* can be defined as a small, discrete task that is required for the assembly of a given product. Thus, the overall operation of assembling a product consists of a number of work elements. For example, one work element in the operation of automobile assembly may be to *attach left door to door hinge* (*on automobile body*). Each work element has a set of work elements that must precede it—it is obvious that the work element *attach left door hinge to automobile body* must precede the *attach left door to door hinge* (*on automobile body*).

Thus, our problem can be modeled as follows:

- Consider an assembly task T_{total} that consists of k different work elements:
- Thus, the total *work content* of the operation, $T_{\text{total}} = \sum_{i=1}^{k} T_i$, where T_i = work element time.
- If we design the assembly line with j workstations, then the sum of the times spent processing the part at the j different workstations must equal the total work content of the operation. Thus, $\sum_{l=1}^{j} T_l = T_{\text{total}}$.
- The time that a product spends at a given workstation is referred to as cycle time T_c. It is the inverse of the production rate of the line. The ideal cycle time is T_{total}/j. However, this assumes that the line is perfectly balanced and that there is no idle time at any stage in the assembly line.
- The rate at which the line produces product is often referred to as *takt time,* or the *heartbeat* of the line.

Following is a summarization of some of the assumptions typically made in the design and balancing of assembly lines [1]:

- The assembly line produces a single product.
- The assembly line configuration is assumed to be straight with serial processing.
- All tasks must be accomplished on the assembly line.
- A task can be processed at any available workstation.
- A task can be assigned to only one workstation.
- Each workstation has the hardware and personnel required to process all tasks.
- All task sequences must respect the precedence relationships.
- The time required to perform each task is known with certainty.
- The time required to perform each task is independent of workstation assignment.
- The time required to perform each task is not sequence dependent.
- The processing time at each workstation is the sum of the task times assigned to the workstation.

Problem Objective

In designing and balancing an assembly line, the industrial engineer must consider: (1) the configuration of the line, (2) the characteristics of the workstations and workers placed on the line, (3) the tasks assigned to the workstations and the workers, (4) the speed of the line. Many work elements are involved in the assembly of a product. Consequently, these work elements are assigned to workstations along the assembly line. Salvenson has pointed out, however, that the design or process characteristics involved in product manufacture mandate that certain tasks must occur in a specific order for proper assembly [2]. The challenge of the assembly line balancing problem is to make work package assignments in such a way as to minimize operating costs or maximize productivity. These decisions must not violate the precedence relationships that exist between the assembly work elements.

The assembly line balancing problem can focus on one of the following three objectives:

1. To find a combination of cycle time and number of workstations, which results in a minimum sum of idle time [3].
2. To reduce labor costs by minimizing the number of workstations on the assembly line. Here, the production rate is known in advance, resulting in a fixed cycle time. An additional constraint is that the processing times at each workstation (determined by the sum of the task times assigned to the workstation) cannot exceed the cycle time [4].
3. To minimize cycle time for a given number of workstations by balancing the line [4].

Evaluating an Assembly Line Design

A good measure of the efficiency of an assembly line is the degree to which it is balanced. The efficiency of an assembly line E can be given by $T_{\text{total}}/T_c * j$. For a perfectly balanced line, the efficiency is 1.

The balance delay D of a line is another indicator of efficiency since it measures the productivity loss in a line: $D = (T_c * j - T_{\text{total}})/T_c * j$.

Some assembly lines are easier to balance than others due to fewer precedence constraints. The flexibility ratio F is a relative measure of the amount of flexibility available in the design of an assembly line [5]. Calculation of this ratio requires the generation of a flexibility matrix. The number of rows (i) and columns (j) of this matrix correspond to the number of task elements in the assembly problem. If task i must precede task j, a 1 is entered at the intersection of row i and column j; otherwise, a 0 is entered at this intersection. The upper right half of the matrix is then used to calculate the F-ratio by the following formula:

$$F = \frac{h}{\text{number of cells in the matrix}} = \frac{2h}{k(k-1)}$$

where h is the number of zeros in the upper half of the matrix, and k is the total number of work elements.

At an F-ratio of 0, there is only one feasible sequence of work elements for the assembly operation. For an F-ratio of 1, all possible sequences (k factorial) are feasible.

Consider the example in Table 17.8.1 that describes some of the tasks associated with a bicycle assembly line (contrived and adapted from Ref. [6]). We see from Table 17.8.1 that it takes

TABLE 17.8.1 Tasks Associated with a Bicycle Assembly Line

Task	Description	Time	Precedence constraint
a	Assemble frame in fixture and weld.	11	—
b	Paint frame.	17	a
c	Bore crankcase.	9	b
d	Install front deraillers.	5	b
e	Install sprocket and crank.	12	c, d
f	Assemble front fork.	8	c
g	Assemble rear wheel and chain.	3	e
h	Install front wheel, handlebar, and adjust.	10	f

12 min to complete task e, and this task must be preceded by tasks c and d. The *F*-ratio of this problem can be evaluated by first developing a flexibility matrix as shown in Table 17.8.2.

TABLE 17.8.2 A Flexibility Matrix

Task	a	b	c	d	e	f	g	h
a		1	1	1	1	1	1	1
b			1	1	1	1	1	1
c				0	1	1	1	1
d					1	0	1	0
e						0	1	0
f							0	1
g								0
h								

The flexibility ratio *F* is given by (2 × 7)/56 = 0.25, which means that there are quite a few feasible sequences available based on the precedent constraints.

The precedence diagram for the work elements in the example problem is shown in Fig. 17.8.1.

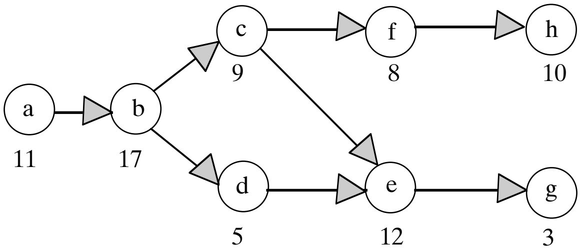

FIGURE 17.8.1 The precedence diagram.

SAMPLE SOLUTION APPROACHES

The first step in solving an assembly line balancing problem is to establish the objective of our solution. For most shop floor situations, the required cycle time has already been established by other factors; thus, our objective here will be to minimize the number of workstations. Most heuristic solutions follow the basic steps of the rank-and-assign heuristics [7]:

Step 1. Start with workstation *i,* where *i* is initially set to 1.

Step 2. Rank tasks from highest to lowest based on numerical scores obtained by intuitively using *one* of the criteria listed in Table 17.8.3.

Step 3. Assign those unassigned work elements with the highest rank to workstation *i.* If the work element selected violates the precedence constraints, or if the total completion time for work at station *i* now exceeds the given cycle time, select the next highest-ranking work element for assignment. (*Note:* If the criterion *element time/slack* is used, the rank of unassigned tasks will have to be recalculated after each work element assignment.)

TABLE 17.8.3 Criteria for Ranking*

Criteria	Description
1. Positional weight	The positional weight of work element *x* is the time taken to complete the element plus the times for all work elements that follow *x*.
2. Number of followers	Sum of the number of work elements that follow work element *x*.
3. Work element time	The time required to complete task *x*.
4. Element time/slack	The time required to complete task *x* divided by the remaining free time (i.e., slack) left in the workstation.

* Highest rank = 1.

Step 4. If the remaining work elements can still be assigned to workstation *i* without the total completion time exceeding the cycle time, then return to step 3. Otherwise, go to step 5.

Step 5. If work elements remain unassigned, and cannot be placed into workstation *i,* then increase *i* by 1 and return to step 3.

Steps 3 through 5 are repeated until all tasks have been assigned. The variable *i* represents the minimum number of workstations required to complete all tasks, given the cycle time. The *rank-and-assign* heuristic can be solved in three different ways. The preceding heuristic is referred to as the *forward assignment procedure.* The preceding example problem is now solved using *positional weight criteria.* We assume that our objective is to achieve a cycle time of 28 min.

Forward Assignment Procedure

1. Positional weight criteria. Actual cycle time achieved is 28 min (Tables 17.8.4 and 17.8.5).

TABLE 17.8.4 Ranking by Positional Weight Criteria

Tasks	Positional weight (score)	Rank
a	11 + 17 + 9 + 5 + 8 + 12 + 10 + 3 = 75	1
b	17 + 9 + 5 + 8 + 12 + 10 + 3 = 64	2
c	9 + 8 + 10 + 12 + 3 = 42	3
d	5 + 12 + 3 = 20	4
e	12 + 3 = 15	6
f	8 + 10 = 18	5
g	3	8
h	10	7

TABLE 17.8.5 Task Assignments (Positional Weight Criteria)

Workstation	Task	Work completion time (TU)
1	a, b	28
2	c, d, f	22
3	e, h, g	25

2. **Number of followers criteria.** Actual cycle time achieved is 28 min TU (Tables 17.8.6 and 17.8.7).
3. **Work element time criteria.** Actual cycle time achieved is 28 min TU (Tables 17.8.8 and 17.8.9).
4. **Element time/slack criteria (Tables 17.8.10 and 17.8.11).**

Iteration 1. Available time for workstation 1 is now 28 – 11 = 17 min. Recalculate the element time/slack (Tables 17.8.12 and 17.8.13).

TABLE 17.8.6 Ranking by Number of Followers Criteria

Task	Number of followers	Rank
a	7	1
b	6	2
c	4	3
d	2	4
e	1	5
f	1	5
g	0	7
h	0	7

TABLE 17.8.7 Task Assignments (Number of Followers Criteria)

Workstation	Task	Work completion time (TU)
1	a, b	28
2	c, d, e	26
3	f, g, h	21

TABLE 17.8.8 Ranking by Work Element Time Criteria

Task	Work element time	Rank
a	11	3
b	17	1
c	9	5
d	5	7
e	12	2
f	8	6
g	3	8
h	10	4

ASSEMBLY LINE BALANCING

TABLE 17.8.9 Task Assignments (Work Element Time Criteria)

Workstation	Task	Work completion time (TU)
1	a, b	28
2	c, f, d	22
3	e, h, g	25

TABLE 17.8.10 Initial Ranking by Element Time/Slack Criteria

Task	Element time/slack	Rank
a	11/17 = 0.6471	3
b	17/11 = 1.5455	1
c	9/19 = 0.4737	5
d	5/23 = 0.2174	7
e	12/16 = 0.7500	2
f	8/20 = 0.4000	6
g	3/25 = 0.1200	8
h	10/18 = 0.5556	4

TABLE 17.8.11 Initial Task Assignment (Element Time/Slack Criteria)

Workstation	Task	Work completion time (TU)
1	a	11

TABLE 17.8.12 Iteration 1 Ranking by Element Time/Slack Criteria

Task	Element time/slack	Rank
b	17/0 =	1
c	9/8 = 1.1250	4
d	5/12 = 0.4170	6
e	12/5 = 2.4000	2
f	8/9 = 0.8890	5
g	3/14 = 0.214	7
h	10/7 = 1.4250	3

TABLE 17.8.13 Iteration 1 Task Assignment (Element Time/Slack Criteria)

Workstation	Task	Work completion time (TU)
1	a, b	28

Iteration 2. Available time for workstation 2 is now 28 min. Recalculate the element time/slack (Tables 17.8.14 and 17.8.15).

Iteration 3. Available time for workstation 2 is now 28 – 9 = 19 min. Recalculate the element time/slack (Tables 17.8.16 and 17.8.17).

Iteration 4. Available time for workstation 2 is now 28 – 17 = 11 min. Recalculate the element time/slack (Tables 17.8.18 and 17.8.19). Available time for workstation 2 is now 28 – 22 = 6 min. However, there is no work element that could possibly be assigned to the workstation 2 based on precedence and time limit.

Iteration 5. Available time for workstation 3 is now 28 min. Recalculate the element time/slack (Tables 17.8.20 and 17.8.21).

TABLE 17.8.14 Iteration 2 Ranking by Element Time/Slack Criteria

Task	Element time/slack	Rank
c	9/19 = 0.4737	3
d	5/23 = 0.2174	5
e	12/16 = 0.7500	1
f	8/20 = 0.4000	4
g	3/25 = 0.1200	6
h	10/18 = 0.5556	2

TABLE 17.8.15 Iteration 2 Task Assignment (Element Time/Slack Criteria)

Workstation	Task	Work completion time (TU)
1	a, b	28
2	c	9

TABLE 17.8.16 Iteration 3 Ranking by Element Time/Slack Criteria

Task	Element time/slack	Rank
d	5/14 = 0.3571	4
e	12/7 = 1.7143	1
f	8/11 = 0.7273	3
g	3/16 = 0.1875	5
h	10/9 = 1.1111	2

ASSEMBLY LINE BALANCING

TABLE 17.8.17 Iteration 3 Task Assignment (Element Time/Slack Criteria)

Workstation	Task	Work completion time (TU)
1	a, b	28
2	c, f	17

TABLE 17.8.18 Iteration 4 Ranking by Element Time/Slack Criteria

Task	Element time/slack	Rank
d	5/6 = 0.8333	2
e	12/(−1) = −12	—
g	3/8 = 0.375	3
h	10/1 = 10	1

TABLE 17.8.19 Iteration 4 Task Assignment (Element Time/Slack Criteria)

Workstation	Task	Work completion time (TU)
1	a, b	28
2	c, f, d	22

TABLE 17.8.20 Iteration 5 Ranking by Element Time/Slack Criteria

Task	Element time/slack	Rank
e	12/16 = 0.7500	1
g	3/25 = 0.1200	3
h	10/18 = 0.5556	2

TABLE 17.8.21 Iteration 5 Task Assignment (Element Time/Slack Criteria)

Workstation	Task	Work completion time (TU)
1	a, b	28
2	c, f, d	22
3	e	12

Iteration 6. Available time for workstation 3 is now 28 – 12 = 16 min. Recalculate the element time/slack (Tables 17.8.22 and 17.8.23). Actual cycle time achieved is 28 min TU.

TABLE 17.8.22 Iteration 6 Ranking by Element Time/Slack Criteria

Task	Element time/slack	Rank
g	3/13 = 0.2308	2
h	10/6 = 1.6667	1

TABLE 17.8.23 Iteration 6 Task Assignment (Element Time/Slack Criteria)

Workstation	Task	Work completion time (TU)
1	a, b	28
2	c, f, d	22
3	e, h, g	25

Backward Assignment and Bidirectional Procedure

In the previous example, tasks were placed into workstations using a *forward assignment procedure* (starting with workstation 1). Alternatively, two other assignment procedures may be used [8]. In the *backward assignment procedure,* the original precedence graph is reversed in its direction of flow (i.e., instead of moving left to right, move right to left). The rank-and-assign heuristic is then applied to the new problem. A third assignment technique is the *bidirectional procedure.* In this approach, a forward rank and backward rank are created for each task. The backward rank is created by simply reversing the flow of the precedence graph, as in the backward assignment procedure. A sufficiently large number of workstations is then created. Using the Bowman example, assume the first workstation is number 1 ($W_F = 1$), and the last workstation is number 6 ($W_L = 6$). For each task, the maximum numerical score that is obtained from either the forward or backward assignment procedure is selected. Then, tasks with the highest numerical score are selected. If the selection was based upon the numerical score from the forward assignment procedure, the task is assigned to the first feasible workstation. Alternatively, if selection was based upon the numerical score from the backward assignment procedure, the task is assigned to the last feasible workstation. If no remaining task can be assigned to W_F, then it is assigned to workstation W_{F+1}. On the other hand, if no remaining task can be assigned to W_L, then it is assigned to workstation W_{L-1}. This process is repeated until all tasks have been assigned. By combining those workstations that contain tasks, a feasible solution is obtained.

ADVANCED TECHNIQUES

Other experimental approaches to solving the line-balancing problem include *simulated annealing* (SA) and *genetic algorithms* (GA). The SA is a random search technique that derives many of its characteristics from the heating and quenching of metals.

As described by Aarts and Korst [9], the three main components of the algorithm are the acceptance criterion, control parameter, and the cooling schedule. A candidate solution is first obtained by moving a task to another workstation or switching tasks between workstations. The acceptance criterion is a probabilistic function that determines whether to accept a new

ASSEMBLY LINE BALANCING

candidate solution. If the candidate solution results in a shorter cycle time, it becomes the new current solution with a probability of 1. If, however, the candidate solution results in a longer cycle time than the current solution, the probability of it being accepted as the new current solution is based on the acceptance criterion. At the start of the algorithm, the SA control parameter is set high enough that virtually all candidate solutions are accepted as new current solutions. As the SA algorithm iterates, this control parameter decreases, decreasing the probability that a poor candidate solution (i.e., one with a slower cycle time than the current solution) will be accepted. The rate of decrease in the control parameter is determined by the cooling schedule. This mechanism gives the SA algorithm the ability to avoid getting trapped in local minima during its search for better solutions.

Another advanced approach that can be used to solve the balancing problem is by the application of the Darwinian principle of natural selection. Known as *genetic algorithms* (GA), these are evolutionary methods of search that can obtain good solutions in multimodal, discontinuous, and noisy response environments [10]. The biologically inspired aspects of this algorithm can be seen in five basic steps [11]. In the first step, a number of solutions are randomly generated. This set of solutions represents the population of a GA. In the second step, each solution in the population is evaluated and assigned a fitness that measures how well this solution satisfies the objective function. The third step entails reproducing solutions for survival based upon their fitness. Reproduction is probabilistic in that the more fit the solution, the more likely it is to be chosen for survival. New solutions are created from the surviving solutions in the fourth step, known as *recombination.* The two forms of recombination utilized by GAs are *crossover* and *mutation.* In crossover, two survivors (i.e., parents) exchange parts of their configurations, which represent their respective solutions. The result of crossover is the formation of two offspring solutions, each of which possesses characteristics of both parents. The second form of recombination is mutation, in which the configuration of a single parent is randomly altered. This mutation results in a new offspring solution, which is different from its parent. In the fifth step, *replacement,* the newly formed solutions become the population of the next generation. Steps 2 through 5 are repeated until a stopping criteria is reached. Genetic algorithms can iteratively evolve increasingly better solutions to a problem while maintaining a diverse population of solutions. This approach helps the search avoid getting trapped at local minima (or local maxima).

Balancing lines manually is feasible when dealing with a limited number of activities, workstations, and resources. When dealing with larger problems, computerized packages that manage data can be applied. An example of such a system is the Assembly Manager™,* by H. B. Maynard and Company, Inc.

ASSEMBLY MANAGER

Today, a variety of computer programs exists for data management and line balancing. These programs provide varied levels of sophistication and complexity, and consequently provide different types of information to the user.

A basic line-balancing program requires the user to input several kinds of information. The first input is a description of the line. At a minimum, the user is typically required to indicate the conditions under which the line balance will occur. Conditions include the total production time, the desired cycle time, and/or the desired production level. Some software will provide the user with the option to automatically determine cycle time and production levels based on the work assigned to each station. A sample screen that identifies program inputs is shown in Fig. 17.8.2.

Next, the user may identify the number of stations on the line. The number of stations is often dictated, or at least limited, by the physical conditions that exist in the facility where

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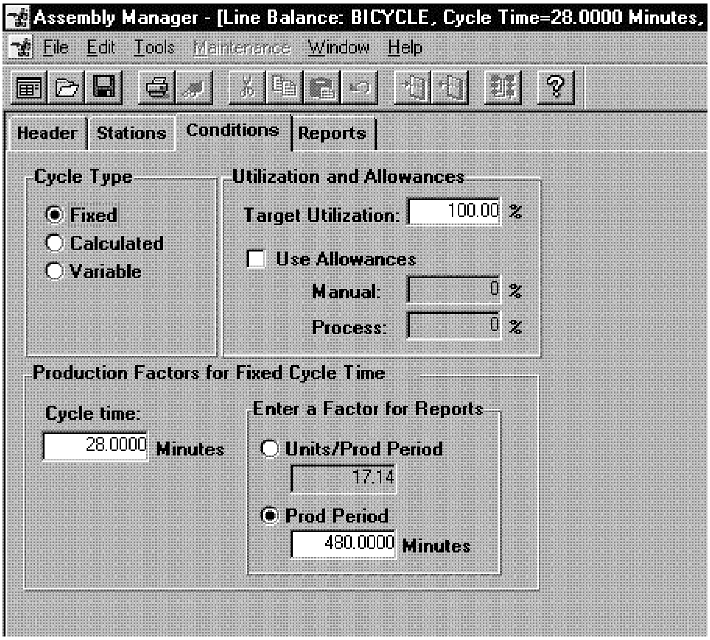
* ™Assembly Manager is a registered trademark of H. B. Maynard and Company, Inc.



Assembly Manager - [Line Balance: BICYCLE, Cycle Time=28.0000 Minutes,

Cycle Type
● Fixed
○ Calculated
○ Variable

Utilization and Allowances
Target Utilization: 100.00 %
☐ Use Allowances
Manual: 0 %
Process: 0 %

Production Factors for Fixed Cycle Time
Cycle time: 28.0000 Minutes

Enter a Factor for Reports
○ Units/Prod Period 17.14
● Prod Period 480.0000 Minutes

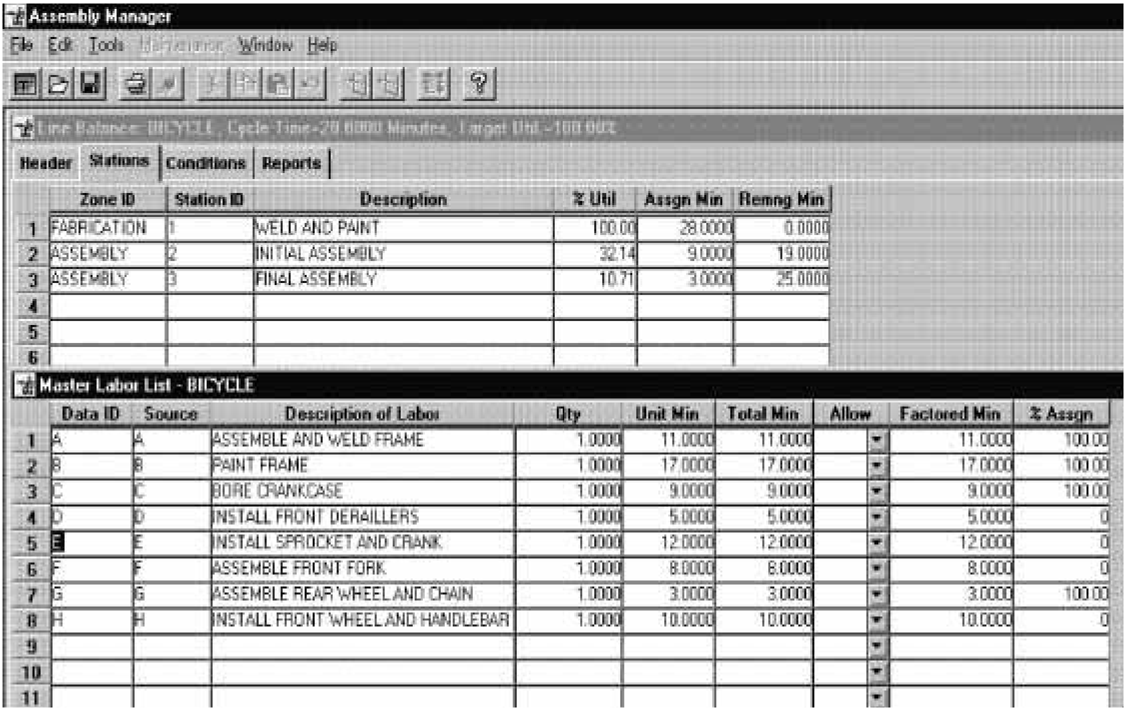
FIGURE 17.8.2 Screen for input of initial information.

the production or assembly line is established. As the number of stations is defined, the user will also indicate the resources available at each station. Resources include things such as the number of operators and any dedicated tools or equipment. Since operators sometimes work at more than one station, or have other responsibilities outside of their work on the line, the number of operators may include fractions. For example, if one operator is shared equally between two stations, the individual would account for one-half of an operator at each station.

Once the line and balance conditions have been defined, the methods and times for completing the work must be identified. Some software packages allow work methods and times to be imported from other databases. This approach is especially beneficial when industrial engineers are already using other systems to set and maintain work standards that, in turn, contain the desired data.

The accuracy, traceability, and flexibility of the data itself determine the usefulness of such standard data. Of course, there is not much point in taking a scientific approach to line balancing if the data used does not accurately reflect the current work methods and times. Furthermore, the data will only be useful for line balancing if it allows for the movement of subsets of data from one station to another. The size (duration) of the data to be moved depends on application. Typically, a shorter cycle time requires movement of smaller pieces of data to achieve the desired balance. Methods must be clearly identified, so that the engineers can easily determine what operation or part of the operation is to be moved from station to station. If reliable data is not available, it should be developed with the previously mentioned requirements in mind. Figure 17.8.3 shows data from the bicycle assembly and fabrication line described earlier, along with an assignment into stations.

Once work methods and times are identified, the work must be assigned to each station on the line. At a minimum, most software allows for the manual assignment of labor to stations as is done in Fig. 17.8.4. Labor is attached to a particular station by typing in a code, clicking,


Assembly Manager
File Edit Tools Window Help
Header Stations Conditions Reports

Line Balance: BICYCLE , Cycle Time=28.0000 Minutes, Target Util=100.00%

	Zone ID	Station ID	Description	% Util	Assgn Min	Remng Min
1	FABRICATION	1	WELD AND PAINT	100.00	28.0000	0.0000
2	ASSEMBLY	2	INITIAL ASSEMBLY	32.14	9.0000	19.0000
3	ASSEMBLY	3	FINAL ASSEMBLY	10.71	3.0000	25.0000
4						
5						
6						

Master Labor List - BICYCLE

	Data ID	Source	Description of Labor	Qty	Unit Min	Total Min	Allow	Factored Min	% Assgn
1	A	A	ASSEMBLE AND WELD FRAME	1.0000	11.0000	11.0000		11.0000	100.00
2	B	B	PAINT FRAME	1.0000	17.0000	17.0000		17.0000	100.00
3	C	C	BORE CRANKCASE	1.0000	9.0000	9.0000		9.0000	100.00
4	D	D	INSTALL FRONT DERAILLERS	1.0000	5.0000	5.0000		5.0000	0
5	E	E	INSTALL SPROCKET AND CRANK	1.0000	12.0000	12.0000		12.0000	0
6	F	F	ASSEMBLE FRONT FORK	1.0000	8.0000	8.0000		8.0000	0
7	G	G	ASSEMBLE REAR WHEEL AND CHAIN	1.0000	3.0000	3.0000		3.0000	100.00
8	H	H	INSTALL FRONT WHEEL AND HANDLEBAR	1.0000	10.0000	10.0000		10.0000	0
9									
10									
11									

FIGURE 17.8.3 Descriptions for bicycle assembly.

dragging, and dropping, or through other similar approaches. One of the major advantages of computer-assisted line balancing is that the program can automatically update statistics for the station and the entire line each time data is moved. This data includes such things as utilization, total assigned time, and total remaining time.

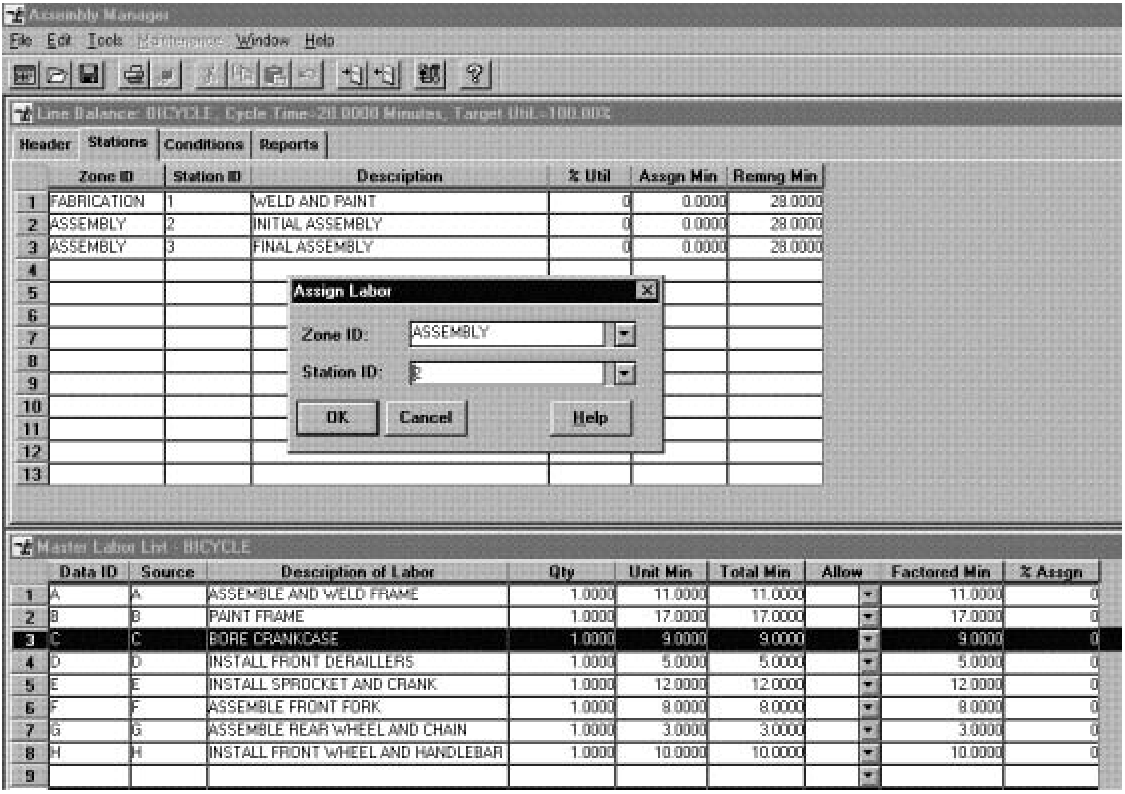
Following the assignment of labor to stations, the software can provide a variety of reporting and analysis capability to allow the industrial engineer to quickly assess the effectiveness of the distribution of labor. The key factors in this analysis are the overall line utilization and loss to balance. These factors measure how equitably work is distributed between stations. The standard time provides the total number of labor-hours per unit.

Targets for utilization can vary greatly, but, in most instances, industrial engineers will attempt to achieve a minimum of 90 percent average labor utilization. Results can appear in textual or graphical formats as is shown in Figs. 17.8.5 through 17.8.7.

Beyond this basic functionality, there are computer applications that take a more sophisticated approach to line balancing in order to further improve the productivity of the line and the engineering function.

Advanced Features

Automatic Assignment of Labor. Some computer applications provide a feature that will automatically assign labor items to stations. These computer programs reference algorithms, similar to those demonstrated earlier in this chapter, to optimize utilization of the resources on the line.



Line Balance: BICYCLE, Cycle Time-28.0000 Minutes, Target Util.-100.00%

	Zone ID	Station ID	Description	% Util	Assgn Min	Remng Min
1	FABRICATION	1	WELD AND PAINT	0	0.0000	28.0000
2	ASSEMBLY	2	INITIAL ASSEMBLY	0	0.0000	28.0000
3	ASSEMBLY	3	FINAL ASSEMBLY	0	0.0000	28.0000
4						
5						
6						
7						
8						
9						
10						
11						
12						
13						

Assign Labor

Zone ID: ASSEMBLY

Station ID: 2

Master Labor List - BICYCLE

	Data ID	Source	Description of Labor	Qty	Unit Min	Total Min	Allow	Factored Min	% Assgn
1	A	A	ASSEMBLE AND WELD FRAME	1.0000	11.0000	11.0000		11.0000	0
2	B	B	PAINT FRAME	1.0000	17.0000	17.0000		17.0000	0
3	C	C	BORE CRANKCASE	1.0000	9.0000	9.0000		9.0000	0
4	D	D	INSTALL FRONT DERAILLERS	1.0000	5.0000	5.0000		5.0000	0
5	E	E	INSTALL SPROCKET AND CRANK	1.0000	12.0000	12.0000		12.0000	0
6	F	F	ASSEMBLE FRONT FORK	1.0000	8.0000	8.0000		8.0000	0
7	G	G	ASSEMBLE REAR WHEEL AND CHAIN	1.0000	3.0000	3.0000		3.0000	0
8	H	H	INSTALL FRONT WHEEL AND HANDLEBAR	1.0000	10.0000	10.0000		10.0000	0
9									

FIGURE 17.8.4 Assignment of labor to workstations.

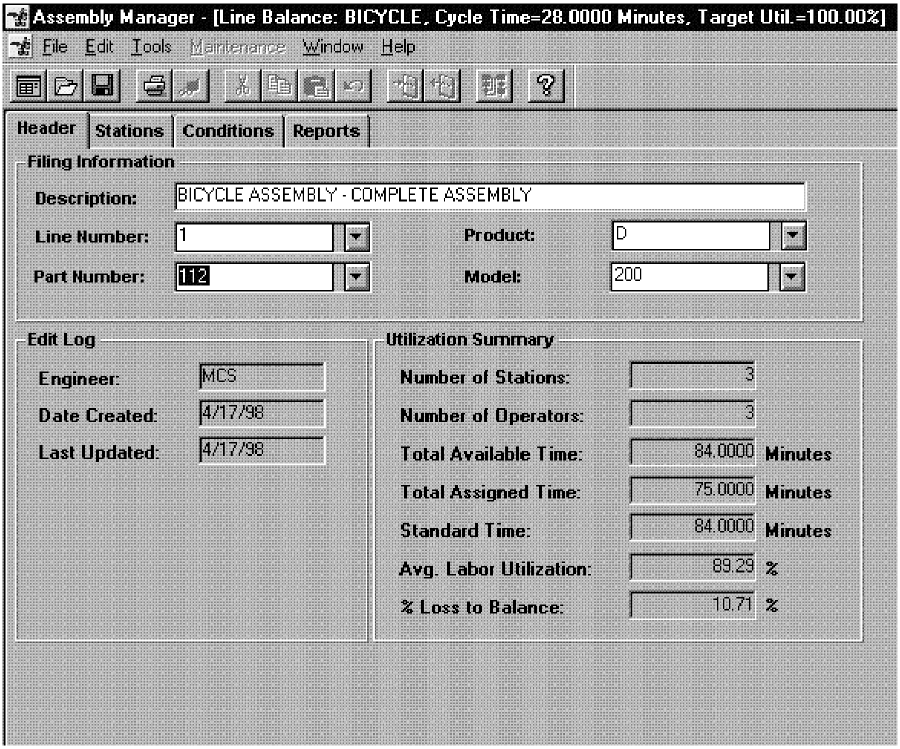
To assign the labor in the proper sequence, the software will enable the analyst to establish precedence, through a precedence list or a base history that tells the software where the labor has been assigned before. While establishing precedence or base history can be a time-consuming process, once completed, it can be used to quickly reestablish a balance based on new or modified conditions.

Model Mix. Oftentimes, several different models and options of a particular product will be produced on the same line. A change in the percentages of each model produced, in relation to total production, is known as a *change in the model mix.*

Software programs that can associate labor with a particular model can automatically adjust the results of a line balance based on the changes to the model mix. This is a powerful feature in a lean manufacturing environment, where model mixes fluctuate on a regular basis, and is described in more detail in the next section.

Early Warning. A unique feature contained in Assembly Manager is called Early Warning. This feature was initially developed for the truck assembly industry, where each unit on the assembly line is significantly different than the units that come before or after it.

Early Warning reads daily production information from a database. It then creates a report that will identify the utilization for each station at intervals of time throughout the coming day, based on that day's specific production sequence.


File
Edit
Tools
Maintenance
Window
Help
Header
Stations
Conditions
Reports

Assembly Manager - [Line Balance: BICYCLE, Cycle Time=28.0000 Minutes, Target Util.=100.00%]

Filing Information

Description: BICYCLE ASSEMBLY - COMPLETE ASSEMBLY

Line Number: 1

Product: D

Part Number: 112

Model: 200

Edit Log

Engineer: MCS

Date Created: 4/17/98

Last Updated: 4/17/98

Utilization Summary

Number of Stations: 3

Number of Operators: 3

Total Available Time: 84.0000 Minutes

Total Assigned Time: 75.0000 Minutes

Standard Time: 84.0000 Minutes

Avg. Labor Utilization: 89.29 %

% Loss to Balance: 10.71 %

FIGURE 17.8.5 Line balancing summary (text format).

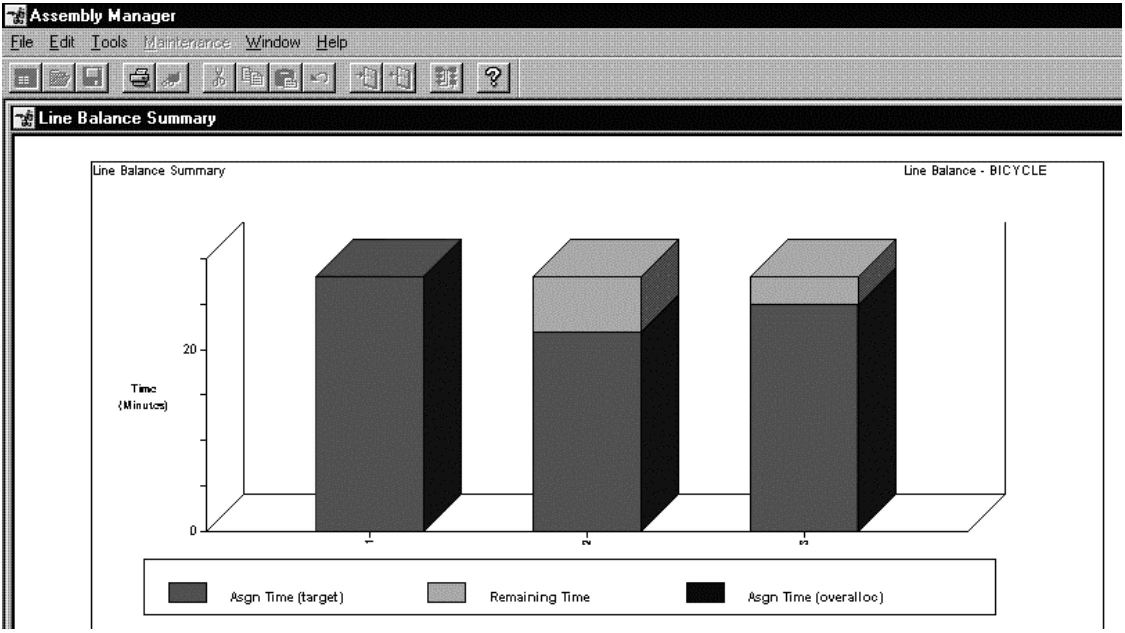
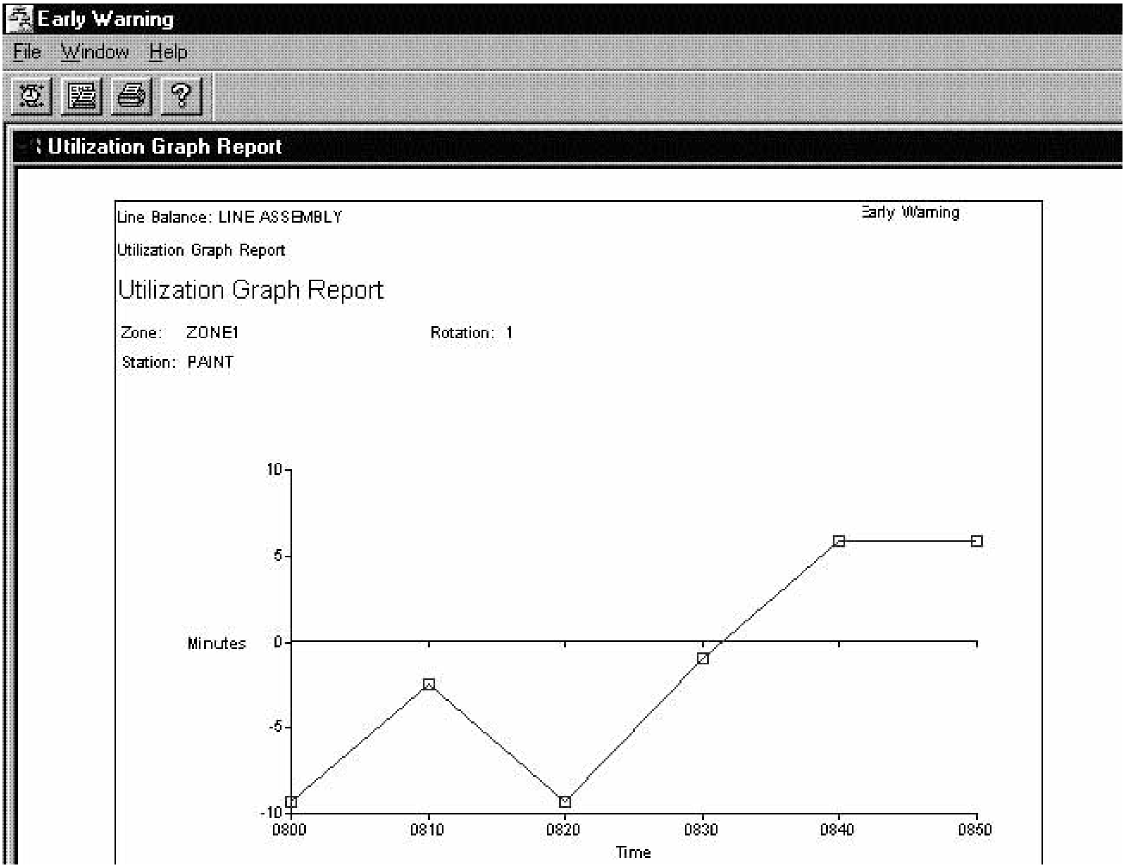


FIGURE 17.8.6 Line balance summary (graph format).


Early Warning
File Window Help
Utilization Graph Report
Early Warning
10
5
0
-5
-10
Minutes
0800
0810
0820
0830
0840
0850
Time

Line Balance: LINE ASSEMBLY

Utilization Graph Report

Utilization Graph Report

Zone: ZONE1 Rotation: 1

Station: PAINT

FIGURE 17.8.7 Utilization graph report.

By indicating the utilization, the report identifies the time of day when staffing problems will exist at each station on the line, thus allowing line management to be proactive and flexible in dealing with the challenges of the day.

Benefits of Computerized Data Management and Line Balancing

In today's manufacturing world, speed and flexibility are of the essence. Many manufacturers run mixed model lines, with model mix fluctuating on a daily basis. To provide necessary support, the industrial engineer must have the tools available to quickly adjust staffing requirements based on the required output.

Software tools can assist industrial engineers in meeting the challenges of today's environment, by providing real-time information to more effectively manage their assembly line resources.

OTHER IMPORTANT CONSIDERATIONS

Mixed-Product Assembly Lines

Sometimes, assembly lines are used to produce a variety of products. It becomes more complicated to balance a mixed-product assembly line. In implementing these lines, a variety of strategies can be established to ensure a high level of performance. When assembling a mix of different products on the same line, a popular strategy is to balance the line by considering the batch size. As the batch size for each product type increases, the mixed-product assembly line begins to resemble a single-product line. Care must be taken to transition from one product to another. Sometimes, products are run in fixed batch sizes with a transition mode. Here, as the new products come through the lines, machines are reassigned, the number of people in the line is modified, and setups are changed. Heuristics, based on product volumes and mix, are available to solve mixed-model lines, though documentation of their applications in industry is limited.

Synchronous Versus Asynchronous Lines

Synchronous lines assume that the entire line moves simultaneously. *Asynchronous lines* are those whose products move from one workstation to the next at different times in the cycle, usually through a buffer. Such lines are difficult to model, and the use of simulation-based models offers an easier means of evaluating what-if scenarios to develop good assignments and sequences. It must be noted that the use of a buffer seemingly increases the efficiency since line balance is not as critical. However, as the number and size of buffers in an assembly line increase, the type of production is also being shifted from the mass production mode to a batch production mode; this brings along other inefficiencies such as longer throughputs and higher inventories. Continuous-type lines resemble a process-type industry (e.g., a refinery), where products *flow* through the line from workstation to workstation without stopping. The heuristics described earlier are applicable in this situation since the line moves at a constant speed.

Practical Tools to Improve Efficiency

In addition to line balancing as a means of increasing efficiency, there are other simple tools that an industrial engineer can use. These include a closer examination of the process plan from the perspective of work elements and individual operations. Sometimes, minor variations in partitioning work elements can lead to a much more balanced line. If one work element is an impediment to achieving the desired cycle time (where $T_{\max}$ > desired T_c), the use of multiple (or parallel) workstations and the bottleneck work element must be explored. Further preparation of the product before it enters the assembly line can be considered as a means of reducing bottleneck work elements.

CONCLUSION AND FUTURE TRENDS

To establish an assembly line, a variety of complex, interrelated factors have to be considered. In addition to the basic work measurement of tasks in the line, the process planning must be complete and unambiguous. Additionally, we have presented the classical heuristics needed to balance an assembly line. Software that helps manage this task is also presented. However, incorporating ergonomic concerns into facility layout design and analysis of the related cost are two factors that must also be considered.

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Bopaya Bidanda is the Ernest Roth Professor and chairman of the Department of Industrial Engineering at the University of Pittsburgh. He is also the codirector of the University's Manufacturing Assistance Center and the Automated Data Collection Laboratory. In addition to his doctoral degree from the Pennsylvania State University, he has industrial experience in manufacturing systems, tools, and precision manufacturing. His research focus includes the areas of computer-integrated manufacturing systems, robotic applications, industrial engineering, automated data collection, and shared manufacturing. He has published widely in international journals and conferences, and he has edited/authored two books: *Automated Factory* and *Shared Manufacturing.* He actively works with manufacturing industries in western Pennsylvania in the areas of cellular manufacturing, work measurement, data collection, and shop floor information systems. He is a senior member of the Institute of Industrial Engineers (IIE) and the Society of Manufacturing Engineers (SME). Dr. Bidanda currently serves as a director of the Pittsburgh Chapter of IIE. He was cochair of the Annual Industrial Engineering Conference for 1998 and 1999.

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Source: MAYNARD'S INDUSTRIAL ENGINEERING HANDBOOK

CHAPTER 17.9

PROJECT MANAGEMENT

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The management of projects has changed substantially over the past 50 years. Many practitioners have not been exposed to these new concepts and techniques. The Project Management Institute, in 1994, issued *A Guide to the Project Management Body of Knowledge,* often referred to as the *PMBOK Guide.* The discussions in this chapter rely heavily on this guide to present concepts and techniques that have proven to be effective in managing projects, regardless of industry, discipline, or size of project. Industrial engineers have the opportunity to lead their organization in the application of modern project management to manage all projects, including methods improvement efforts, development of new processes, quality improvement programs, new construction, and the hiring and training of personnel. As in the introduction of any new methods, the industrial engineer must ensure that he or she has the best possible information and advice in installing project management.

INTRODUCTION

D. E. Peterson, while president of Ford Motor Company, called a meeting of some 500 Ford executives and suppliers to introduce quality management as he had learned it from Deming. Peterson purportedly began his opening remarks something like this: "It's going to be hard for you to accept that you were promoted for the wrong reasons a time or two. . . . I had the experience (in a recent meeting) that most people in the room thought I was talking about something so elementary that we, of course, already do it at Ford Motor Company. They could not understand why I was talking about it. It left me with the sense that many of us still do not understand what we are really trying to change" [1].

It is easy to imagine a similar statement being made today about project management. You may think you understand project management but you may not understand it as well as you think. Two things have happened over recent years. A series of developments that started in the 1950s in construction and defense industries has matured into a well-defined profession, sometimes referred to as modern project management (MPM). The discipline is now being applied in practically every field of endeavor. One need only glance through Tom Peters' *Liberation Management* to realize that projects or project management is mentioned in nearly every chapter, if not every page. Indeed, in the index, these subjects take up a whole column—half a page [2].

While most of the early developments focused on computer technique development, recent developments have focused broadly on how to achieve both efficiency and effectiveness in project planning and execution. *A Guide to the Project Management Body of Knowledge* (*PMBOK Guide*) [3] has been developed that identifies the knowledge that is unique to managing projects. Indeed, all the essential elements of a profession are in place including certification of individuals, accreditation of educational programs, a code of ethics, and a body of literature discussing the theory and practice of project management. The Project Management Institute (PMI), the professional society for project managers, has been growing at rates in excess of 30 percent per year for the last two years and is recognized worldwide for its services to project managers. One of those services is the publication of the most current information on concepts, techniques, and practices of modern project management. Thus, PMI materials will be cited frequently in what follows as the most current sources of information.

Two of the most recent PMI publications are *The Benefits of Project Management* [4] and *Best Practices of Project Management Groups in Large Functional Organizations* [5]. The former uses a maturity model and regression analysis to document significant benefits of MPM in terms of both cost and schedule performance.

In the past, chapters on project management in this handbook have focused on techniques. While this has been quite appropriate, it has promulgated the notion that these techniques are the essence of project management. While computer techniques are essential in the modern world, they have now become a relatively small portion of the PMBOK. Consider that computer techniques permit planning and scheduling to be accomplished with much less time and effort invested, permitting more time to be allocated to the other aspects of managing the project.

Additionally, these techniques enable projects to be planned and executed with a great deal more precision. Thus, new approaches to managing are essential to realize the benefits of these new techniques. It is helpful in comprehending this difference to consider the difference between a sledgehammer and a sculptor's hammer. In the past, projects were often managed by the sledgehammer approach. Many projects are still managed in this manner. One executive confessed that he feared that he did not know how to manage any other way. Today, changes in society's and people's attitudes toward work have made it essential to develop approaches to managing projects that are more akin to the sculptor's hammer—a tool used with skill and precision.

That is the essence of MPM—using the skills and precision that are possible with the new techniques and knowledge that are included in the PMBOK.

Thus, this chapter will begin with an overview of the PMBOK followed by a discussion of the most relevant techniques applicable to managing most projects. There are many ways to become familiar with the use of these techniques and more than one should be used. But first let us ensure that we have a common understanding of project management concepts.

PROJECT MANAGEMENT CONCEPTS

The Concept of Projects

Projects and project management may be one of the more misunderstood concepts in management. This is due in part to opinions developed in the early days of the new concepts and in part to the fact that projects have been a way of life throughout history.

The first published developments in MPM were sponsored by DuPont and the U.S. Navy followed closely by the U.S. Department of Defense (DoD) and National Aeronautics and Space Administration (NASA). From these efforts, the impression was given that the techniques were applicable in construction and maintenance (in the case of DuPont) and to very-large-scale defense and space systems development. This impression has been promulgated by authors of textbooks in production/operations management, management science, and operations research. With the advent of a variety of microcomputer-based project scheduling software and the availability and convenience of use of these packages, projects of all sizes have benefited from their application.

In the early years of MPM, the cost of application was substantial for two reasons: user friendliness and training of users. The first systems were not user friendly. Considerable computer expertise was required and the methods for using these techniques were inherently labor intensive. Today, both of these deficiencies have been overcome. User friendliness has made it possible for novices to use significant features of a package with only a few hours of introduction, generally from the user's manual, help messages, or tutoring programs. Training in the use of project management techniques has become widespread and many persons with project management responsibilities find it easy to plan their projects using an on-line mode, with considerable benefit coming from a better understanding of the project and more accurate communication of their desired approach for the execution of the project.

Project efforts have been described early in recorded history. The change efforts of society are conducted by projects. Most managers and engineers have been involved in, and many have managed projects. The degree and scope of responsibility has typically been rather limited and shifted from one individual to another as the project progresses through its various phases. Thus, many people have had experience managing projects. It is entirely possible that this experience was not consistent with the needs of MPM.

Projects Are Temporary. "A project is a temporary endeavor undertaken to create a unique product or service." This is the definition of *project* as found in PMI's 1994 *A Guide to the Project Management Body of Knowledge* [3]. *Temporary* means that every project has a definite ending point. *Unique* means the product or service is different in some distinguishing way from all similar products or services.

Project *Is Not Synonymous with the* Product of the Project. The word *project* is often used ambiguously, sometimes referring to the project and sometimes referring to the product of the project. This is not a trivial distinction because both entities have characteristics unique to themselves. Some of the concepts apply to both. For example, the life cycle of a project typically includes the conceptual, development, implementation, and termination phases. The life cycle of a capital facility—the product of a project—includes feasibility and acquisition (a project), operation, major repairs or refurbishing (typically done as projects), and dismantling (often a project, if done at all). The project cost of creating the capital facilities to produce a product is generally a relatively small proportion of the life cycle cost of that product (see Fig. 17.9.1).

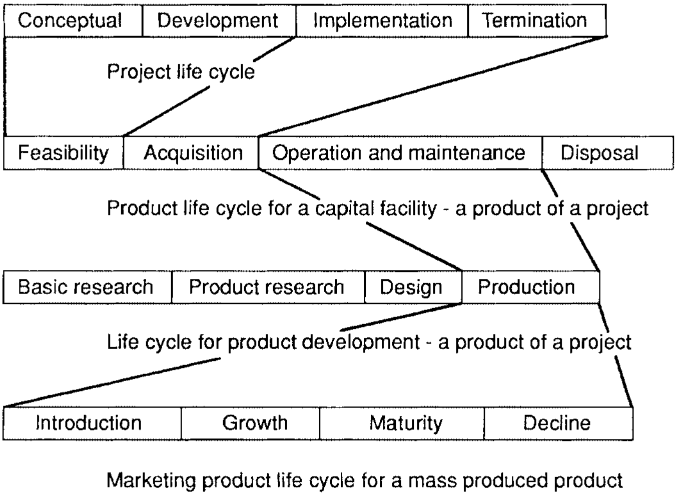
Conceptual
Development
Implementation
Termination
Project life cycle
Feasibility
Acquisition
Operation and maintenance
Disposal
Product life cycle for a capital facility - a product of a project
Basic research
Product research
Design
Production
Life cycle for product development - a product of a project
Introduction
Growth
Maturity
Decline
Marketing product life cycle for a mass produced product

FIGURE 17.9.1 Life cycles.

Similarly, there is a life cycle of product development consisting of basic research, product research, design, and production. The first three are projects. The objective of the production phase is typically to prolong the useful life of the product, often done through understanding the phases of the marketing product life cycle.

Projects Are Accomplished by Progressive Elaboration. Because projects are unique, the essential process for both the project and the product of the project is *progressive elaboration.* Often the product of the project begins with a very general statement such as, "We should build a house." Over time this statement is elaborated into specifications, drawings, purchase of specific materials, selection of colors, and so on until the house is occupied. Often final details are completed some time after that. For commercial products, as-built drawings are generally produced to show exactly how it was produced. Concomitantly, the project plans are developed in a similar manner, showing increasing details as the product is further defined. Often the project planning process will reveal significant problems in producing the product leading to changes in both the product and the project plans.

Projects Are Composed of Activities. These activities are usually nonrepetitive, operating on an interrelated set of items that inherently have technologically determined relationships. While some aspects of a project involve repetitive production techniques, even they often vary from project to project. The restriction of *an interrelated set of items* implies that there is a set of activities that are necessary and sufficient to produce the product of the project. Omitting any of these activities leads to additional risk and possibly rework. Any additional activities add unnecessary work content, and therefore cost, to the project. *Technologically determined relationships* implies an ordering of activities on the project. For example, one activity must be completed before another can begin. These relationships are described in the network diagram.

Projects Involve Multiple Resources. Project resources, both human and nonhuman, require close coordination, more so than in the typical job shop. Generally there is a variety of resources, each with their own unique technologies, skills, and traits. This leads to an inherent characteristic of projects—conflict. There are conflicts between resources as to concepts, theory, techniques, and so forth. There are conflicts for resources as to quantity, timing, and specific assignments, along with other sources of conflict in projects. Therefore, a project manager must be skilled in managing conflict.

THE MANAGEMENT OF PROJECTS

Managerial Emphasis

Managerial emphasis is on timely accomplishment of the project as compared with the managerial emphasis in other modes of work (more so than in the typical job shop). Most projects require the investment of considerable sums of money prior to enjoyment of the benefits of the resulting product. Interest on these funds is a major reason for emphasis on time. Being first in the market often determines long-term market position, thus creating time pressure. Finally, a need exists for the resulting product of the project; otherwise, the project would not have been authorized. Time is of the essence.

Project Management Is the Management of Change

This leads to one of the anomalies of project management. While project management is the management of change, change is the most difficult part of project management. It is inevitable that during the process of progressive elaboration, learning takes place. It is recognized that a slight modification of the product would make it more user friendly or applicable to a wider range of users and thus a larger market. Or it is recognized that a different method for performing an activity in the project can provide reduced costs or increased quality. These changes usually have implications on work that has already been accomplished or on work that is now or soon will be in process. Extreme care and patience is required to understand these implications, determine how to deal with them, and communicate them adequately to prevent errors in the project.

Relation to Modern Quality Management

The preceding characterization of projects permits the adaptation of modern quality management concepts into the management of projects. Modern quality management begins with conformance to requirements/specifications.

The relevance of *conformance* can be made no clearer than as presented in the first nine pages of Chap. 4 in *Quality is Free* [6]. To begin, there must be a clear understanding of customer/client requirements in a product. These then become the specifications for the next stage. This process continues throughout the project until the product of the project is completed. If new knowledge leads to changes in the requirements/specifications, they must be formally incorporated into the project plan.

Another important concept is zero defects or, "Do the right thing right the first time." Repeated experience has shown that more attention to doing jobs right the first time eliminates so much rework, and scrap costs, as to fully support the proposition that quality is free.

When these concepts are combined with another essential concept of modern quality management, a new perspective on the project as a process is available. This perspective comes from the customer, who is the next person/operation in the process. Thus, as the progressive elaboration of specification proceeds, the "customer" is the next engineer, tool builder, ad layout person, and so on. If the product going to them has no defects, they can perform their tasks in the most efficient manner—and get it right the first time.

Given this concept of a project, as a process it is essential to apply process control, and more specific, statistical process control, to the management of projects. One approach to this was presented in the article "Validating Technical Project Plans" [7]. It involves procedures for reviewing the plans for a project in much the same manner as design or construction review teams analyze the design of a product for such things as structural integrity or constructability. Reviewing the project plans focuses on feasibility and sequences of activities, identifies risks and needs for coordination, and assesses personnel skill requirements required, among other things.

Another approach was outlined in "Reliability Maturity Index" [8]. This concept identified events in a project network that marked the completion of activities that either measured or contributed to the reliability of the product of the project. Other concepts/techniques were identified in "Responsibility for Quality in Project" [9] including failure mode and effect analysis, fault tree analysis, and stratified random sampling. Still others involve the development and application of methods/technologies that permit the operator on a project to perform inspections on the product immediately upon completion or even during the performance of an operation.

THE PRACTICE OF PROJECT MANAGEMENT

PMI's *A Guide to the Project Management Body of Knowledge* published in 1994 is a complete reworking of the 1987 version [10]. While most of the concepts and terms remain the same, two things are different. As might be expected, reflecting early efforts to codify a body of knowledge, there were inconsistencies in the document. These have been corrected. More important, the emphasis has changed from a *reference* orientation to a *systems* orientation. Thus, it captures the essence of the flow of information and work as a project progresses, including the often iterative nature of the process as new knowledge is gained and changes occur. It must be understood that this guide does not present the body of knowledge but rather catalogs the relevant knowledge and provides a framework for understanding the interrelationships of the various components of that knowledge.

The PMBOK Guide defines the essential terms and concepts that a person needs to understand to earn certification as a Project Management Professional. It is organized into 12 chapters. The first 4 chapters, discussing the Project Management Framework, are titled Introduction, The Project Management Context, The Process of Project Management, and Key Integrative Processes. The next 8 chapters focus on the Project Management Knowledge Areas of Scope, Time, Cost, Quality, Human Resource, Communications, Risk, and Contract/Procurement Management. Six appendices provide additional information including a Glossary. The following discussion of the application of project management is based on this PMBOK Guide.

The Project Management Framework

Introduction. The introduction provides an overview of the entire document, as well as definitions of fundamental terms such as *project.*

Project Management Context. The project management context begins by developing the concept of the project life cycle. This concept is similar to product life cycle and has often been characterized in terms of four phases: conceptual, design, execution, and closeout. As the application of MPM has spread to more industries, recognition has been given to a more general concept of the project phases. Emphasis is now placed on understanding why phases are useful in managing a project and adapting the life cycle to the needs of an industry, organization, or individual project.

Project stakeholders are defined as "individuals and organizations who are actively involved in the project, or whose interest may be affected by it" [3]. The project manager is responsible for managing the relations between the project and all stakeholders.

There are also discussions of the alternative organizational concepts for projects, key general management skills, and socioeconomic influences.

Process of Project Management. This chapter provides the general flow of work and information to establish the relationships between the eight basic areas and each of their next level components. These flowcharts provide the project manager with a framework for the systems view of project management processes and a general road map to follow in managing a project.

Key Integrative Processes. Key processes are project plan development, project plan execution, and overall change control. Each of these is discussed in terms of the inputs, tools and techniques, and outputs. It is an excellent guide for the project manager to use to ensure that all elements of the management process have been considered. Integration of the efforts of other project team members is the key role of the project manager.

Project Management Knowledge Areas

Project Scope Management. The first step in any project should be the development of a charter. This should, at a minimum, identify and document the objectives of the project—the characteristics of the product of the project that is being proposed and any stipulations about how the project is to be conducted. This is discussed under Authorization. Other divisions of project scope management are scope planning, scope definition, scope change control, and scope verification.

A strategy is then chosen by which the project is to be undertaken and it is expressed in a work breakdown structure (WBS). The WBS is "a product-oriented family tree of project components which organizes and defines the total scope of the project. Each descending level represents an increasingly detailed definition of a project component. Project components may be products or services." The lowest level of the WBS is a work package. It is a more precise and disciplined way to identify the tasks in a project than the familiar back of the envelope.

It is important that the scope of a project be carefully defined for at least two reasons: omission and commission. Errors of omission result in the client being unsatisfied with the product of the project. Errors of commission, while perhaps leading to greater client satisfaction, can easily result in work being performed for which proper compensation is not received.

Errors of omission may be recognized prior to completion of the project. If discovered early enough, their impact may be negligible. If not, they can result in significant tearup and rework. They may result in extra costs, inadequate performance of the product of the project, and, worst of all, litigation to resolve disputes over the delays, extra costs, or performance inadequacies.

Errors of commission may enter the project in the scoping process by mistake or on purpose. In a large, complex project, miscommunication may lead to work being incorporated that is not really necessary or intended. Additional work may be incorporated in the project at lower levels in the organization to avoid risks. Even after the project scope is approved, additional work can creep into the project as a result of direct contact between the client and those responsible for performing specific activities. For example, in a software development effort, the client may persuade the programmer to introduce extra features in the software without proper recognition of the resulting change in work content, both directly and indirectly. When this takes place, the contractor is not likely to be compensated for the extra work. Furthermore, these changes may well result in failures in testing and integration later in the project.

Change control procedures are a must to ensure that all changes to the project scope are documented, checked for adverse consequences, approved (including for payment if appropriate), and adequately communicated throughout the project team.

Project Time Management. Time management consists of five essential processes: activity definition, activity sequencing, duration estimating, schedule development, and time control.

Given the five steps in time management, it should be apparent that scheduling is a separate process. It may be less than apparent that activity definition, sequencing, and estimating *should not* be done concurrently with scheduling. Doing all four of these at one time is a habit, that has carried over from planning with a Gantt chart. That tool invited doing planning and scheduling concurrently. The risk of this approach is that, not understanding the interrelatedness of some activities, a schedule will be developed that is inherently inefficient. It is better to wait until the planning is essentially completed, make the first computer schedule analysis run, and use the information that is developed to aid in proper scheduling.

Until after the first schedule analysis, the planner does not know which path through the network is critical. For example, on one system development project, the critical path was composed, in part, of some 50 activities that involved intracompany mail. Each activity was estimated at three days. It was an easy decision to have mail on such critical paths hand carried. It would have been foolish to make that decision prior to knowing that intracompany mail, clearly the cheapest, was not appropriate for some activities. Generally, such revelations are more substantive in nature, but often can be just as surprising to the project planner.

Activity Definition. Using the WBS, the lowest level elements (work packages) are further defined, specifying the activities necessary to complete the work package. This process is similar to producing a list of operations in preparing manufacturing instructions. A major part of this process is writing a description of the activity, just as on a processing instruction. Typically in manufacturing the variety of processing steps is limited, permitting the use of forms and relative shorthand notation for describing the operations. In projects, the variety of activities is greater, necessitating a greater reliance on prose for these descriptions.

Activity Sequencing. Activity sequencing involves identifying the technological relationships between the activities in a project network diagram, similar to an assembly line balloon chart. Care must be exercised to avoid inserting relationships that are preferences rather than technological requirements. Otherwise the scheduling process will be unnecessarily constrained leading to a less than optimal schedule. This process may require updating the activity list, such as splitting activities or recognizing tasks not originally recognized in creating that list.

Duration Estimating. The number of work periods likely to be required to perform each activity is estimated. An inability to estimate accurately should never be an excuse for not using modern scheduling techniques for three reasons. First, the degree of accuracy is independent of the technique used; it is inherent in the projects we undertake. Second, the network approach to planning inevitably leads to a better understanding of the project, and therefore better estimating than comes with the use of any other planning and scheduling technique. Third, the errors are likely to be distributed randomly and therefore balance out to some degree.

Due to the unique nature of projects, the typical approaches to estimating used by industrial engineers in volume production situations are generally not applicable. For an organization that performs similar projects repeatedly, it may be useful to develop standard jobs in a manner similar to that used in setting standards for maintenance tasks.

Inherent in the estimating process is the determination of the work content in resource hours, the units of resource that will be applied, the utilization and productivity of those resources, and, in many instances, the skill level of the specific resource relative to the specific activity. Environmental circumstances affect these estimates, including the weather, hazards, and uncertainties associated with hidden elements such as underground conditions. The work climate of the organization can affect these estimates, so the estimator must be aware of factors contributing to organizational climate.

There are two theories as to who should do the estimating. One approach is for the person most directly responsible for performing the activity to make the estimates. This leads to greater psychological commitment to the estimates. A favorable work climate *can* result in consistently optimistic estimates, which may have to be tempered by management. If the work climate is unfavorable, estimates will likely be "padded" in order to avoid the unpleasant consequences of failing to complete the activity in the estimated time.

The other approach to estimating is to use a professional estimator who is more likely to provide an unbiased estimate. The professional estimator's estimates are less likely to be biased if there is an incentive associated with on-time completion of activities.

Schedule Development. A plan represents how one intends to execute a project without regard to when the project will be executed. The schedule—planned start and finish dates for each activity—applies the recognition of time and resource constraints.

The conflict between time and resource constraints is inherent and must be resolved. A project will not get done by management dictum if the time and/or resources are less than required. The discussion of resource management techniques details the difference between time-constrained and resource-constrained scheduling. One will be controlling in any project and will determine the feasible completion time for the project.

Time Control. Time control is "concerned with (a) influencing the factors which create schedule changes, (b) determining that the schedule has changed, and (c) managing the actual changes when and as they occur" [3].

The most popular method of measuring performance is by percent complete. This is subject to the adage, "It takes 90 percent of the time available to complete 90 percent of the work and it takes another 90 percent of the time available to complete the last 10 percent of the work." Some practitioners have adopted a practice of placing a limit on the maximum duration of activities and then accepting reports of progress only in terms of completed activities. This becomes particularly poignant when payment for work accomplished is based on completed activities. Another approach is to have the responsible person simply answer "yes" or "no" to the question, "Are you on time?" It should be clear that the question applies to the activity being started on time as well as to it being completed on time. Failure to start on time is the first indication that the activity will likely be late. Failure to complete an activity on time following a stream of "yes" answers can be very embarrassing. A "no" answer on intermediate progress reports should not be scorned as it is an indicator that action may be required by management, but considered as an indicator of possible problems that can still be corrected. Precipitous reaction to unfavorable progress reports can have serious consequences, resulting in inaccurate reports of progress or excessive reliance on management to effect the solution.

Project Cost Management. Project cost management includes the "processes required to ensure that the project is completed within the approved budget" [3]. While primarily concerned with the cost of the project, it frequently considers nonproject costs as well. For example, while omitting one design review meeting could reduce project costs, it might result in an increase in the product operating costs and thus increase the life cycle cost of the product. Cost management is discussed under four headings: resource planning, cost estimating, cost budgeting, and cost control. While discussed separately for clarity, there is generally a high degree of interaction in the application of these processes. The person performing this must be familiar with the resources, their capabilities, organizational policies and attitudes, and historical performance on similar efforts.

Alternative methods for performing an activity must be considered to select the most cost efficient one.

Resource Planning. Resource planning involves "determination of what physical resource (people, equipment, and materials) should be used to perform project activities" [3]. Care must be exercised in determining the skill and experience level required. The cost of performing an activity can vary greatly depending on the match of skill and experience required versus that applied.

Estimating. Estimating concerns "developing an approximation (estimate) of the costs of the resources needed to complete project activities" [3]. They are generally expressed in monetary terms to provide comparisons and summation. However, for closer control, it is desirable to record the elements from which the costs are derived, such as labor and equipment hours, unit costs, and productivity measurements. These permit the exercise of control on a more immediate basis such as daily performance reports.

Budgeting. Budgeting requires "allocating the cost estimates to individual work packages in the WBS in order to establish a cost baseline for measuring project performance" [3]. The work packages are the lowest level at which accounting accumulates actual costs. This forms the basis for the cost baseline and the spending plan.

One of the important uses of the information developed in this step is the measurement of expenditures over time. By accumulating the costs over all activities by time period, a histogram of expenditures is derived. If these costs are accumulated over all time periods the result is an *S* curve of cash flow (See Illustration 17.9.9 in the section on Project Management Techniques.) If the project is performed to schedule, expenditures should flow along this curve.

Another use for the data developed in the budgeting process is cash management. This is particularly vivid on government projects where the funding is approved year by year, requiring speeding up the project one year and stretching it out the next. By changing the completion date of the project and scheduling the activities appropriately, the S curve will become steeper when accelerating the project and flatter when stretching the project out.

Control. Control is concerned with (a) influencing the factors that create differences from the cost baseline, (b) determining that such differences have or are likely to occur, and (c) managing the activities to minimize the unfavorable differences and maximize the favorable ones. It includes developing revised estimates, and if appropriate, seeking approval of budget updates.

Cost control, or management, must be considered from four points of view: financial accounting systems compatibility, the concerned party, the timing of costs, and current cost control.

FINANCIAL ACCOUNTING SYSTEMS COMPATIBILITY: One of the most difficult problems involved in realizing adequate project cost control is achieving compatibility with the accounting system in the organization. Unless the organization operates primarily in the project mode, the accounting system likely will be oriented toward one of the other four modes of work efforts, namely, craft, job shop, progressive line, or continuous flow process. This will cause conflict. Many accounting systems are established primarily to accommodate the requirements of financial accounting. Many of the practices involved in financial accounting do not meet the needs of timely project cost control. Even in accounting systems with strong work order systems there is often a tendency to collect costs at a more summary level than is generally required for adequate project cost control.

If the aforementioned situation exists in your organization, special efforts may be necessary to achieve adequate control. For example, on some projects it may be advantageous to make a copy of all labor distribution reports prior to submission to accounting. Labor-hours are attributed to activities or work packages and priced at standard rates. Copies of all invoices are used to record payments to others. Other costs are dealt with in a similar manner. Monthly reconciliation is done and correcting entries made to negate variances. It is extra work but sometimes necessary to achieve control on projects that are moving too fast to wait on the normal accounting data. Alternatively, control can be exercised over the resources used on the project and let the dollars fall where they may.

THE CONCERNED PARTY: The major theory for cost management on projects is *earned value.* Earned value as a concept can be characterized as the standard cost concept applied to projects. The implementation of earned value is well documented in publications by the Department of Defense and others who have officially adopted this theory. Such publications may be referred to as Cost/Schedule Control Systems Criteria, or C-Spec or C/SCSC.*

C/SCSC presents the current requirements derived from what started as program evaluation and review technique (PERT)/cost. For a variety of reasons, including its lack of flexibility, PERT/cost did not work in practice. C/SCSC was developed to provide more flexibility. Over time it has been adapted to ensure accurate and proper accounting for projects. This author's sardonic view of C/SCSC is that it is an attempt to close the loopholes by which contractors have, in the past, billed for costs that were not justified. This view is derived, in part, from the anecdotes recounted in a very good book on the subject by Fleming [11].

C/SCSC is primarily a client's costs management system, that is, it provides assurances to the client that payment is not being made for work that has not been done. To the extent that project managers are clients of subcontractors, earned value is certainly a useful tool. On very large projects, it provides the project manager an overview of costs. No such system should be considered adequate for effective cost management to the exclusion of "managing by walking around" and other more immediate measures of cost.

THE TIMING OF COSTS: If the project manager relies solely on the typical accounting system to manage the cost on the project, it will be too late and cost overruns will likely be inevitable. The typical accounting system recognizes costs when they are actually paid—when the check is written. In non-project-oriented organizations this is often as much as 45 days after the performance of a given activity or the delivery of materials or equipment.

At minimum, the cost should be recognized when the work is performed or the delivery is received. Many project managers have resorted to collecting actual labor hours on a daily or weekly basis, extending them by some standard or average rates, and entering them in the project cost system immediately. This requires later reconciliation adjustments but that is better than not being aware of costs for a considerable period of time. Similarly, costs on materials and equipment can be entered directly from the invoice rather than waiting for it to make the rounds through the accounting system.

The best management of project costs is achieved if they are recognized when they are committed. Many organizations manage costs based on a committed cost control concept. While specific implementations will vary, the basic concept is to recognize that a cost is incurred at the time when the purchase order is released, a work order is authorized, or a similar event has occurred. The significance of this is easily seen when the lag between signing a purchase order and the writing of the check to pay for the purchased item is recognized. For major equipment items, this lag may be more than a year. If control is not exercised until the check is written, additional commitments can result in serious overruns. In organizations that do not have a formal committed cost control system, managers often maintain supplementary records manually to ensure they do not overcommit authorized funds.

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* This has recently been superseded by the ANSI/EIA 748 Guide with slightly relaxed specifications.

The author is not aware of any project schedule/cost control systems commercially available as of late 2000 that provide true commitment cost control.

CURRENT COST CONTROL: The emphasis on earned value concepts could lead one to believe that such a system would be adequate to control costs on a project. A more realistic approach recognizes that costs are controlled by careful planning, communication, observation, and correction on a daily, if not an hourly, basis. Measurement of accomplishments each day and careful comparison to planned accomplishments provides information that can be used to make corrections before further efforts are expended. For example, in pouring a concrete retaining wall, the amount of concrete can be determined by measuring the forms and recording the amounts received in each truckload as compared with the amount budgeted. Labor costs can be measured for the pour and compared with standards derived from similar work. Performance comparisons can thus be available before the next day begins. Most construction firms and other companies that normally work in the project mode have developed their own in-house systems for recording and measuring each day's production and having the results available the next day to permit corrective action as appropriate.

Effective cost management must be current. It must be done on a day-by-day basis just as it is on the shop floor of a manufacturing operation. This capability does not seem to exist in any commercially available software for project management.

Current cost control on projects can also be enhanced through the use of conventional industrial engineering techniques such as work sampling and methods studies. Work sampling can measure the frequency of delays of labor and equipment due to manageable causes such as lack of material or instructions, waiting on equipment, and breakdowns. Work methods can be applied at the planning stages of the work. For example, in constructing a wood frame house, there are many opportunities to introduce modern methods, jigs, and fixtures that can provide substantial reductions in work content to accomplish a specific task. It would seem that most skilled tradespeople lack training in the application of work methods analysis.

Project Quality Management. This involves the "processes required to ensure that the project will satisfy the needs for which it was undertaken. It includes all activities of the overall management function that determine the quality policy, objectives, and responsibilities and implements them by such means as quality planning, quality assurance, and quality improvement, within the quality system." These "processes must address both the product of the project (what is produced) and the process of the project (how the product is produced, i.e., how the project management processes are performed)" [3].

- *Quality planning* involves "identifying which quality standards are relevant to the project and determining how to satisfy them" [3]. The major sources of standards are those imposed from external sources. An organization should have internal policies and standards.
- *Quality control* concerns "monitoring specific project results to determine if they comply with relevant quality standards and identifying ways to eliminate causes of unsatisfactory results" [3]. It includes acceptance decisions and monitoring rework. It should be noted that rework costs are often a major portion of a project's costs, thus placing a real premium on processes to ensure that the work is done correctly the first time.
- *Quality assurance* is "all the planned and systematic activities implemented within the quality system to provide confidence that the project will satisfy the relevant quality standards" [3]. The primary outputs of this process are quality improvements, both in the product and the project, that is, the processes for creating the product.

It should be noted that the nonrepetitive nature of projects implies that many decisions will have to be made for a specific project. For the same reason, many of the process improvements may have little or no impact on the current project due to the lead time in their implementation versus the relatively short duration of the activities in the project. Many improvements will have to be justified on the basis of their applicability to future projects.

Project Human Resource Management. This includes the "processes required to make the most effective use of the people involved with the project. It includes all the project stakeholders, sponsors, customers, individual contributors, and others" [3]. There is a large body of general literature on this subject but it must be adapted to recognize the temporary nature of the project. The personal and organizational relationships on the team will generally be temporary, new, and often more varied than in the typical organization due to the varied professional disciplines of the members as well as their experience in their home organizations. There are three subdivisions in human resource management: organizational planning, staff acquisition, and team development.

Organization Planning. While the project management strategy is represented in the WBS, it is implemented through people. A major concern of that strategy is the management of interfaces . . . technical, organizational, and interpersonal. It is necessary to find the right people to manage the top-level elements of the WBS. Often, an understanding of the technical interfaces, and their inherent conflicts, will provide insights into the organizational and interpersonal conflicts. Careful organizational planning can facilitate the management of these conflicts.

The outputs of this process include the organization chart, along with a staffing plan and role and responsibility assignments. It is helpful to use a responsibility/accountability chart to aid in analyzing and communicating the latter.

Staff Acquisition. Staff acquisition means "getting the human resources needed (individuals or groups) assigned to and working on the project" [3]. It is in this process that the project manager's networking skills will be most beneficial. First, it is important to know the capabilities, characteristics, interests, and availability of the pool of resources. Without this, it will be very difficult to avoid the poor performers, let alone getting the best performers, assigned to the team. If at all possible, try to retain the prerogative of using resources external to the organization if internal staff offered is deemed inadequate.

Team Development. Because project teams are temporary, special measures must be taken to ensure that they operate as a team. Collocation may be preferred but often is not feasible. In the absence of collocation, team building is even more important. Team building can vary from an agenda item in a regular team meeting to an extended, off-site meeting. The essence of the process is to help team members to know and understand each other's capabilities, needs, and prejudices as well as to accept a common vision of the project. The more successful the team development, the more likely team members will all be pursuing the same objectives for the project. Training on any special characteristics of the project such as a unique technology or specific systems to be used on the project will also be helpful.

Reward and recognition systems have become accepted as key to achieving high performance of the project team. This is especially important on project teams as responsibility for the team member's individual performance evaluations are likely to be retained by their functional manager. The range of the techniques is broad but the critical aspects are keeping the rewards very visibly associated with well-recognized events in the project and relevant to the team members involved.

It is important to recognize that human resources management on a project must be performed within the constraints of the policies and procedures of the parent organization, and often other organizations. The output from all of these efforts, but especially from team development, is improved performance on the project.

Project Communications Management. Communications management "provides the critical link among people, ideas, and information that are necessary for success" [3]. The uniqueness of projects reduces the opportunity to predefine how every processing step is to be performed, especially if the organization generally does not often undertake the particular type of project. Thus, many of the techniques relied on to achieve common perceptions in volume production environments are not practical on projects. Ad hoc meetings, documents, and designs are more prevalent as means of communication. This area is divided into four sections: communications planning, information distribution, progress reporting, and administrative closure.

- *Communications planning* involves "determining the information and communications needs of the stakeholders: who needs what information, when they will need it, and how it will be given to them" [3].
- *Information distribution* implements the communications plan, plus responds to unexpected requests for information.
- *Progress reporting* "provides the project stakeholders with information about how resources are being used to achieve project objectives" [3]. It includes status as well as performance reporting and should also provide forecasts for the future where that may have an impact on the stakeholder, such as street closings.
- *Administrative closure* consists of "verifying and documenting project results to formalize acceptance of the product of the project by the sponsor, client, or customer. It includes collection of project records, ensuring that they reflect the final specifications, analysis of project success and effectiveness, and archiving such information for future use" [3]. This should be an ongoing process throughout the project to avoid errors of omission.

Communications has often been the most neglected area on projects. It has been something that was done when time was available and then often begrudgingly. The increasing concerns and involvement of the public in projects, as well as legal implications, have made it imperative that a much higher priority be placed on communicating. The history of nuclear energy generating stations is sufficient to make this evident.

It is important to communicate the project vision, plans, schedules, and even attitudes to members of the project team to ensure optimum progress. The project network diagram and a Gantt chart schedule are only two of several vital tools in this process. It is important to communicate with the client to ensure expectations are being met and that expectations are kept in perspective—that they do not escalate or disappear. If the importance of the project wanes, support will disappear, and the project is probably doomed to failure. It is also important to communicate with the public on many projects to ensure that false hopes and fears do not lead to reactions that are detrimental to the project. Proactive communications are critical to project success.

A number of articles have appeared in *PM NETwork* illustrating the importance of communicating with the various publics of a major project. One of these articles, "The Milwaukee Water Pollution Abatement Program, Its Stakeholder Management," shows how effective public relations solved many problems before they reached crisis proportions and gained public support for the project [12]. Another, "The Westlake Story: The Need for Coordination, Cooperation and Communication," describes how coordination and cooperation were achieved through effective communications [13].

On the other hand, care must be exercised that project team members are not overloaded with information to the extent that absorbing it impedes progress on the project. Communications planning can aid in preventing errors of both omission and commission. Care must also be exercised in the review of progress to encourage honest reporting or progress. *Honest reporting of problems should never be criticized. Failure to report problems should be a most serious offense.*

Project Risk Management. This concerns the "processes concerned with identifying, analyzing, and responding to uncertainty. It includes maximizing the results of positive events and minimizing the consequences of adverse events" [3]. The PMBOK divides risk management into risk identification, risk quantification, response development, and risk control.

- *Risk identification* "consists of determining what sources of risk and which risk events may reasonably be expected to affect the project" [3]. Legal risks involve licenses, patent rights, contractual failure, suits, both insider and outsider, and force majeure. Technical risks may involve state-of-the-art technology, new applications of proven technology, or simply differences from usual quality, productivity, or reliability. Internal nontechnical risks can result from schedule delays, cost overruns, or cash flow problems. External predictable risks may involve economy and market forces, operational problems, or environmental or social impacts. External unpredictable risks include natural hazards, regulatory problems, and failure of other organizations, such as a governmental failure to complete necessary related facilities or services.

- *Risk quantification* is "primarily concerned with determining which risk events warrant response" [3]. The probability of each risk event is estimated, possible outcomes of each risk event are identified, the probability of each outcome estimated, and the cost or benefit of each determined. From this, expected values can be calculated. Judgments can be made on the basis of the expected value but should also consider whether the worst case can even be tolerated.
- *Response development* is deciding specifically what action should be taken. One possible action, especially where the consequences are intolerable, is to spread the risk through insurance including direct property damage such as auto collision, indirect consequential loss such as business interruption, legal liability such as property damage arising from another's negligence, and personnel concerns including employee bodily injury. A response system should be put into place to ensure that appropriate action is taken should the risk be realized.
- *Risk control* involves "executing the risk management plans in order to respond to risk events over the course of the project" [3]. Sophisticated risk analysis is rapidly becoming an integral part of project management. The most frequently used aspect of this is measuring the time uncertainty in a manner similar to that developed in PERT. However, a more accurate approach is taken today based on Monte Carlo simulation. This approach, contrary to PERT, considers the impacts of all paths through the network to the event in question. Thus, reasonably valid statements can be made about the probability that a project, or intermediate milestone, can be completed by a given target date. If the probability is too low, the target completion can be renegotiated to a later date or the plan revised to increase the probability to an acceptable level. Such considerations are of increasing relevance in multiproject programs where the results of the program cannot be realized unless all projects are completed per schedule.

Project Procurement Management. This area deals with "acquiring goods and services from outside the immediate project organization" [3]. It is composed of procurement planning, solicitation planning, solicitation, source selection, contract administration, and contract closeout.

- *Procurement planning* is similar to the make-or-buy processes in manufacturing. Complicating factors include the time pressures inherent in projects, the often short-term relationships with the supplier, the importance of getting it right the first time, often working from partially defined requirements in the beginning, and the uncertainties often encountered, such as hidden conditions in excavation work.

  A clear understanding of the objectives of the project as manifest in the scope of work, the project strategy, the environment, and the risks is essential. Much of this can be reflected in the contract work breakdown structure, which identifies relationships between WBS elements and their interfaces. There is no better documentation of this than in "Endicott Oil Field: First Offshore Arctic Oil Field Begins Production" [14]. The construction of this offshore Arctic production and processing facility 20 miles east of Prudhoe Bay exemplifies the best use of contracting strategy to complete a $1-billion-plus contract nine months ahead of schedule and $600 million under budget. Oil production started only weeks after the arrival on a barge of a gas compression module (5160 tons, 96 feet wide, 195 feet long, and 105 feet high) from its erection site on the Mississippi River in Louisiana.
- *Solicitation planning* includes "preparing the documents needed to support solicitation" [3] and establishing the evaluation criteria. Often this entails determining the minimum requirements to be an eligible bidder.
- *Solicitation* requires "obtaining information (bids and proposals) from prospective contractors on how project needs can be met" [3]. The uniqueness of projects and time pressure often create conflicts between meeting the needs of the project and good procurement practices. The project manager must recognize this and anticipate project requirements and work with procurement staff to ensure a positive relationship.

PROJECT MANAGEMENT

- *Source selection.* The problems in this area are most vividly portrayed by the purported comment of the astronaut who observed that the spaceship was composed of thousands of items, all provided by the lowest-cost vendor. Project personnel often work directly with a specific vendor in determining how project needs will be met and thereby limit procurement in the source selection process. One strategy used effectively by a builder was to develop a "family of subs" to establish a bilateral relationship of dependency on each other. Inherent in this process is negotiation of price, delivery, work performance, and many other issues, whether the procurement is from outside sources or from functions within the parent organization. Thus, negotiating ability is an essential skill of project managers.
- *Contract administration.* It is not reasonable to contract for a portion of a project and then assume that it will be done in accordance with all requirements. Contract administration requires the maintenance of all documents associated with the procurement to ensure that all legal provisions are met and to provide evidence in the event of a legal dispute. The emphasis should be in gaining cooperation so that there are no delays and no disputes. A significant part of this is in change management. It is the rare project that is completed exactly as originally planned.
- *Contract closeout* is "similar to administrative closure in that it involves both product verification (was all work completed correctly and satisfactorily) and administrative closeout (updating of records to reflect final results and archiving of such information for future use)" [3]. Clearly, the more attention paid to this during the project, the easier this will be at the end of the project. The final step in the contract should be formal notification to the contractor that the contract has been completed.

PROJECT MANAGEMENT TECHNIQUES

A Taxonomy

To establish the framework for discussion of the techniques available for managing projects, it is desirable to define a taxonomy of techniques. There are two classes: critical path techniques (CPT) and other project techniques (see Fig. 17.9.2).

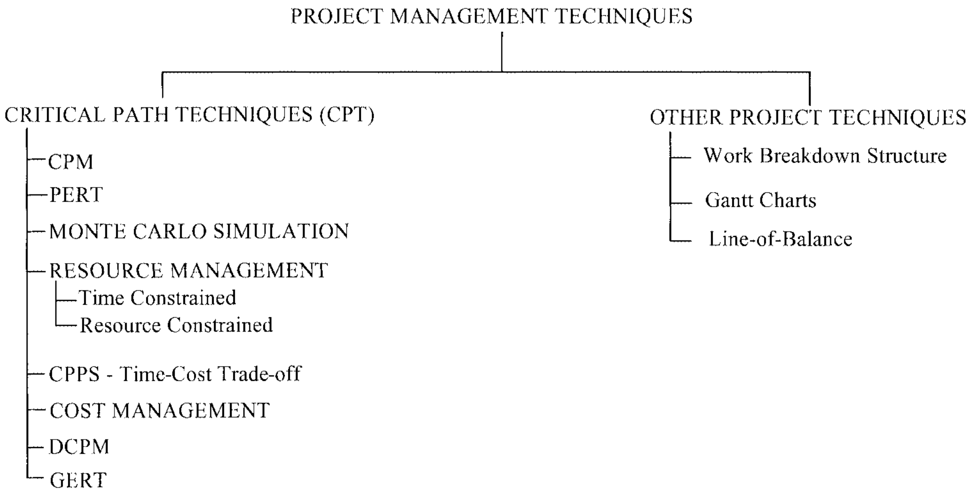

PROJECT MANAGEMENT TECHNIQUES
CRITICAL PATH TECHNIQUES (CPT)
CPM
PERT
MONTE CARLO SIMULATION
RESOURCE MANAGEMENT
Time Constrained
Resource Constrained
CPPS - Time-Cost Trade-off
COST MANAGEMENT
DCPM
GERT
OTHER PROJECT TECHNIQUES
Work Breakdown Structure
Gantt Charts
Line-of-Balance

FIGURE 17.9.2 Taxonomy of project management techniques.

All of the critical path techniques have two things in common, they are (1) network diagram based and (2) involve the calculation of early and late times for the performance of each activity necessary for the performance of the project. These need to be understood before proceeding to a detailed discussion of the techniques. Thus, the next section presents some fundamentals of networks.

Fundamentals of Networks

A *project network diagram* is a schematic display of the sequential and logical relationship of the activities that compose a project. Generally, the technological relationships are very difficult to violate. For example, if getting dressed is considered a project, it just does not make sense to put your shoes on before your socks. Whether to put on both socks and then both shoes or to complete the left foot before the right foot is generally a question of preference. In MPM, a network diagram is used to portray these technological sequences. Figure 17.9.3 illustrates the use of networks to describe alternative ways of putting on socks (RSock and LSock) and shoes (RShoe and LShoe).

Figure 17.9.3(A) does not imply that both socks are put on simultaneously but rather it provides flexibility to determine the actual sequence based on other criteria. It is important

A. RSock → LSock → RShoe → LShoe → Done

Serial network with preference for putting both socks on first and doing the right foot before the left foot.

B. RSock → RShoe → LSock → LShoe → Done

Serial network with preference for putting sock and shoe on right foot first.

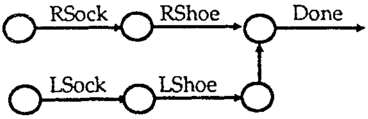
C. RSock → RShoe ↘
Done
LSock → LShoe ↗

Parallel network with only technological relationships.

D. RShoe → LShoe → LSock → LSock

A nonsensical network, in most instances.

(a)



(b)

FIGURE 17.9.3 Illustrations of network diagrams.

for planners to focus on the technological relationships to prevent implicitly scheduling a project before really understanding the alternatives available.

Figure 17.9.3(D) would be nonsensical in most instances because not only does it imply putting the sock on over the shoe but also suggests putting both socks on the left shoe.

Project Network Diagram Conventions. For several reasons there has developed a great deal of ambiguity of the language of networking. PERT networks, critical path method (CPM) networks, and precedence diagrams are sometimes referred to as if they are unique and sometimes as if they were synonymous. It is helpful to develop a clear distinction that can be described by a 3D matrix with the dimensions being graphic convention, focus convention, and identification convention as shown in Fig. 17.9.4.

Graphic Convention. Project networks can be graphically portrayed in either activity-on-the-node (AON) or activity-on-the-arrow (AOA) notation. The examples in Fig. 17.9.3 are shown in AON notation. An example of AOA notation, based on Fig. 17.9.3, network C would be

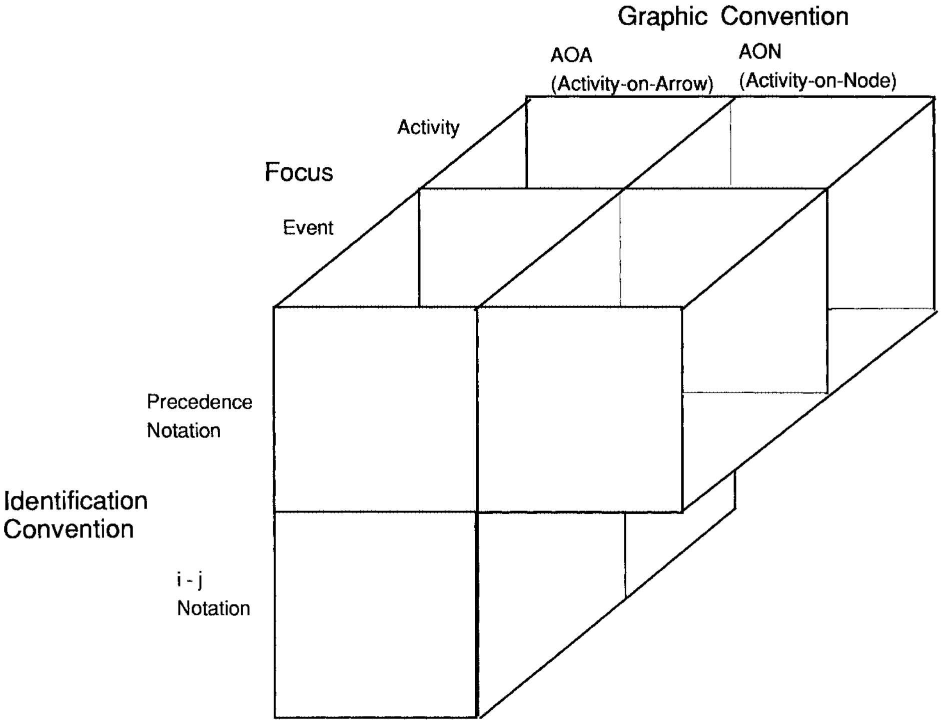


FIGURE 17.9.4 Project network diagram conventions.

The original development of both PERT and CPM were based on AOA notation resulting in AOA being the notation learned by most users. While the AON convention was developed at about the same time, it was not until the personal computer versions of critical path techniques that AON started becoming really popular in the United States.

There are a number of reasons for preferring AON, including ease of use, separating planning from scheduling, and ability to maintain the integrity of identification of activities as they are subdivided when adding more detail. Probably the greatest benefit to industrial engineers, however, is that it is exactly the same notation used in drawing process flowcharts, computer program flowcharts, and precedence (balloon) diagrams in assembly line balancing. Thus, AON requires less learning time and is less likely to result in errors.

This does not mean that the AOA notation has no usefulness. After planning a project using AON, it is useful to check the logic of the plan by plotting an AOA diagram on a timescale to see the temporal relationships between activities. Often it is possible to recognize that an activity is scheduled at what seems to be a totally illogical time. This can easily happen in a complex project because a precedence relation was inadvertently not specified or a relationship was specified that was really not necessary.

Most CPT software packages today have the ability to plot the project in either AOA or AON modes.

Focus Convention. PERT and CPM were developed for completely different purposes and therefore focused on the project in a different manner. PERT, as its name implies (program evaluation and review technique), was developed to assess the probability that a specific event could take place as scheduled; the focus was on the *event.* CPM was developed to improve the planning and control of the work on a project. Indeed, the original development resulted in the critical path planning and scheduling (CPPS) technique that focused on the time-cost trade-off inherent in scheduling the project in a shorter total duration. (This is discussed in more detail in the section entitled CPPS—Time-Cost Trade-off).

Thus, from the beginning, these two techniques had a difference in focus. Each has its place in MPM. Top executives, in planning corporate strategy and approving projects, are primarily concerned with schedules, "When is it going to be completed!" Generally, they have too many other details on their minds to consider much more than the major milestones of the various projects ongoing in the organization. A common axiom suggests that no more than three milestones on a project should be reported at a briefing of top executives lest they become confused from information overload. Recent interest in "prudency," especially in utility rate cases, has lead top executives to take more interest in the major projects in their organization.

Identification Convention. Both PERT and CPM, as originally developed, used the same method of identifying activities in a network, the "i-j" convention—events were given identifiers, usually numbers, and an activity was denoted by the number of the predecessor event followed by the number of successor event such as: 110–130.

The systems developed with AON notation used what is commonly referred to as *precedence notation.* Early on, these systems permitted the use of alphanumeric codes to uniquely identify activities (instead of events). Thus, an activity can be given the code name ABCDE or AESS. The relationship between two or more activities can be specified by simply listing the activity of concern followed by its predecessor(s):

AESS – ABCDE, 34567, CM12P

which states in coded form that AESS cannot start until activities ABCDE, 34567, and CM12P are completed.

Another alternative permits listing the followers of an activity, and, today, some systems allow both follower and predecessor notation in the same project. In the past, some knowledgeable persons argued for a nonmeaningful code, which lead to something like ABCDE. More recently, it has become accepted practice to use a meaningful code such as AESS, which might stand for "Erect structural steel in area A." Recently developed software provides several characters for identifying activities, making it quite easy to develop a standardized coding structure for activities commonly performed in an organization. This provides at least two benefits: ease of recalling the names of frequently used activities and the ability to compare like activities across projects to improve estimating, performance, and measurement.

Overlap. In addition to the preceding conventions, other logical relationships are available. The original planning logic permitted only one basic logic between activities: the follower of an activity could not start until the preceding activity was finished. This proved quite frustrating in accurately portraying relationships where the follower could clearly start before the predecessor was finished. Thus, four alternative logics were introduced and are popular today. They are

1. Finish-to-Start with overlap/delay—[B A(FS-3 days)]—activity B can be started three days before activity A is finished or for [B A(FS + 3 days)] activity B cannot start until three days after A is finished. The former is useful to indicate that detail drawings can be started three days before the layout drawings are completed. The latter would be convenient for indicating that the forms cannot be removed from a concrete wall until three days after it was poured.
2. Finish-to-Finish with overlap/delay—[B A(FF + 3)]—is convenient to indicate that it is permissible to start activity B before A is finished, just do not expect to finish it until three days after B is finished.
3. Start-to-Start with overlap/delay—[B A(SS + 3)]—is an alternative way to state that work can start on detail drawings three days after layout drawings have started.
4. Start-to-Finish with overlap/delay—[B A(SF + 3)]—is perhaps somewhat less useful but the logic is available in many systems today.

While these overlap capabilities are very useful in many situations, they can be overused. A network incorporating many of these relationships can be very confusing and thus diminish its ability to communicate. Manual calculations are much more involved, reducing the ability to analyze the network. Finally, it is easy to incorporate logic that has unintended consequences. Indeed, in the extreme, it has been shown that it is possible to construct a project network that shows a project's finish time that is before its start time. With these thoughts in mind, it should be easy to remember to use these relationships with discretion.

EXAMPLE: For purposes of explanation, we have developed a simple project that is used to illustrate each of the techniques. At each step we introduce only those aspects that are unique to that technique. The data are presented in AON, precedence, and work focus notation. The explanation of each technique is presented in the accompanying illustrations so the reader may skip it in reading the rest of the text. There are many other sources that provide explanations of the other variants. A description of the example project is shown in Illustration 17.9.1.

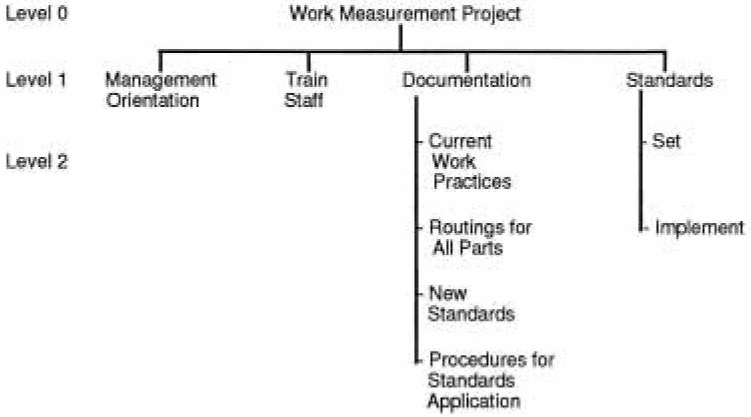
Estimating. Estimating in projects is somewhat more involved and less precise than most estimating done by industrial engineers. For one thing, the unique nature of projects limits the usefulness of past data, makes time study of the job less applicable, and in general reduces the cost-benefit ratio of engineered time standards. In addition, it is often necessary to differentiate between the work content of an activity and the actual duration that will be required. For one thing, it is generally not certain exactly who will perform the activity. One person may be very skilled at doing the activity but the person who ends up doing it may be much less skilled. Often, one person works on more than one activity at a time; thus, the work content must be divided by less than a full workday to determine the actual duration. Much project work is performed with little supervision, resulting in varying degrees of efficiency on the same activity. Communications of exactly what is expected as the work product of the activity may be incomplete. In addition, some activities may be pushing the state of the art of the technology and, therefore, may be dependent on repeated trials, or even serendipity, to find the solution to a difficult problem.

These factors tend to focus on estimating durations. Inherent in an estimate is an assumption of the methods/technologies that will be used. In addition, there are resource types to select, including not only human resources but also the supplies and equipment required. There is uncertainty involved in all of these practices. Cost estimates must be derived that

You have been assigned the task of installing a work measurement program in your organization. To get this program established you have chosen to plan a project to develop standards in the worm gear department, anticipating that other departments will follow on and the program will be operational.

WBS

The first step is to develop a Work Breakdown Structure (WBS) which defines the scope of this project. The following represents your perception of the project.



For ease of referencing these elements, use the first letter of the elements involved. For example, "W" represents the project at Level 0, "D" represents documentation at level 1, and "R" represents routings for all parts level 2, giving "WDR" as the identifier or name of that activity.

NETWORK

The next step is to develop a network to show the logical relationships between these activities. You decide that the management orientation and training can start at the same time. Documenting current work practices can start after the management orientation and staff training. Documenting routings and setting standards can start as soon as the current work practices are documented. Documenting the new standards and the procedures for their application can start as soon as the routings are documented. Implementation can start as soon as the standards are set and the procedures and new standards are documented. It might be represented as follows.

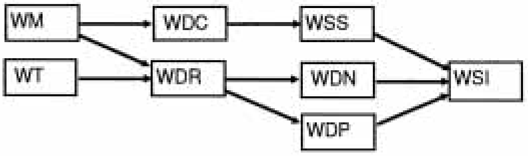
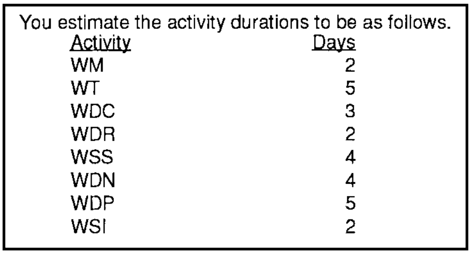


ILLUSTRATION 17.9.1 Example project/establish a work measurement program.

could, if too high, result in the project not being approved, or if too low, result in poor performance to budget, schedule, and/or meet technical requirements. (See Illustration 17.9.2.)

Network Calculations. Network calculations are tedious but quite simple to master with a little practice. Any user of a computer program to perform these calculations is urged to invest the time and effort necessary to be comfortable with these manual calculations for at least three reasons. First, it is risky to accept computer output as accurate without knowing the basis for the calculation of that output. Surprises can happen! Second, the computer output will be presented in tabular format and it is important that the user be able to read that output and interpret it properly. Third, many years of experience teaching the network approach



You estimate the activity durations to be as follows.

Activity	Days
WM	2
WT	5
WDC	3
WDR	2
WSS	4
WDN	4
WDP	5
WSI	2

ILLUSTRATION 17.9.2 Estimating.

to planning has indicated that most persons do not inherently think in terms of a complex network and require some training such as is involved in learning the calculation procedures. (See Illustrations 17.9.3 and 17.9.4 for further discussion.)

Critical Path Techniques

Critical Path Method (CPM). For the purposes of discussion, *CPM* will be used to refer to the simplest form of critical path technique (CPT) involving the precedence relationships between activities, a single estimate of each activity's duration, and the calculation of early and late start and completion times, and total slack. This distinction is important because of the ambiguity that exists in literature. If one refers to the typical textbook on management science/operations research, production/operations management, or industrial engineering, CPM will probably refer to the time-cost trade-off algorithm. If one speaks with practitioners in the field, CPM will probably refer to the simplest system as defined here. We prefer the vernacular of the practitioner.

Program Evaluation and Review Technique (PERT). PERT was developed by a team representing the Naval Weapons Research Laboratory and Booz-Allen consultants to evaluate the status of the Polaris Missile Weapons System [15]. It was originally developed to permit the expression of the uncertainty associated with moving from one event to another. Considerable mathematics was used in deriving the specific form of the distribution, the beta, and the practical simplification leading to three time estimates: a = optimistic or shortest reasonable time, m = most likely time, and b = pessimistic or longest reasonable time. The original PERT relationship assumed that a and b occurred about one time in a hundred each. The three time estimates were used to calculate a mean and standard deviation for each activity as follows:

$$t_e = (a + 4m + b)/6$$

where t_e is the expected value of the duration of the activity as in expected value theory in probability and statistics:

$$\sigma = (b - a)/6$$

where σ is the standard deviation of the distribution of activity's duration.

The general logic of the calculations is identical to CPM except for the calculation of t_e for the duration and the calculation of the standard deviation of the ending event or activity. While the theory of PERT assumes a beta distribution (i.e., one that may be skewed to either the right or the left), the central limit theorem nevertheless allows the addition of the activity distributions on the critical path with the resulting distribution assumed to approximate the normal curve of probability theory. Thus, the mean of the ending activity or event is equal

It is necessary to add the predecessor information to the table to define the logic of the network. To calculate the feasible time frame for each of these activities, start with time zero for those activities having no predecessor. Time zero can be interpreted as the end of day zero. Add their durations to their start time to get the finish time. The finish time for WM can be interpreted as the end of day 2. WDR has two predecessors, WM and WT. WDR cannot start until both of the predecessors are completed, i.e., the end of the 5th day. Proceed in a similar manner for the remaining activities. Note that WSI cannot start until after the end of the 12th day, after all three of its predecessors are completed. **The rule is: When calculating the early times, always choose the latest finish of the activity's predecessors.**

Act	Pred.	Days	ES	EF
WM	-	2	0	2
WT	-	5	0	5
WDC	WM	3	2	5
WDR	WM,WT	2	5	7
WSS	WDC	4	5	9
WDN	WDR	4	7	11
WDP	WDR	5	7	12
WSI	WSS,WDN,WDP	2	12	14

When calculating the late starts and finishes it is necessary to have a target completion date for the project. This target date could be arbitrarily chosen, perhaps by management, and could be either earlier or later than the earliest finish of the project, i.e., 14 days. On this project you have been given a target date by management of 13 days. Otherwise, ignore the early calculations while doing the late calculations.

From the network diagram it is clear that WSI is the ending activity. Give it the target finish time of 13. Subtract the duration to get the latest start time of 11. Post that 11 as the latest finish time of activities WSS, WDN, and WDP as they must be finished before WSI can start. Proceed up the list completing the calculation and posting of one activity at a time. After posting WDP's late start of 6 to WDR's late finish, WDN shows a late start time of 7. Since the 7 is later than the 6, ignore the 7 and proceed. **The rule is: When calculating the late times, choose the earliest start time of the activity's followers.**

Act	Pred.	Days	LS	LF
WM	-	2	2	4
WT	-	5	-1	4
WDC	WM	3	4	7
WDR	WM,WT	2	4	6
WSS	WDC	4	7	11
WDN	WDR	4	7	11
WDP	WDR	5	6	11
WSI	WSS,WDN,WDP	2	11	13

Completion of these calculations discloses a problem as activity WT's late start time is 1 which means it should have started yesterday if the target completion date is to be met. This calls for replanning.

ILLUSTRATION 17.9.3 Calculations.

to the sum of the means of the activities on the longest path leading to that activity or event. Similarly, the variance of the ending activity or event is the sum of the variances (standard deviations squared) of the activities on that same path. The square root of the summed variances is the standard deviation of the completion time for that activity or event. Generally, this is done only for the latest activity or event in the project. Thus, substituting the three time estimates for each activity in the example network, the calculations are as shown in Illustration 17.9.5.

The resulting t_e of 13 is the expected completion time for the last activity or event on the critical path. There is a 50 percent chance it will take more time to complete the project but also a 50 percent chance that it will take less time.

PROJECT MANAGEMENT

Reviewing the plan, we decide that the documentation of application procedures can be finished after the implementation has started so long as it is finished at the end of that activity, i.e., WDP and WSI can complete at the same time, the completion of the project. Combining the early and late calculations into one table gives the following. The only difference in these calculations is due to the removal of WDP as a predecessor to WSI.

							TOTAL	FREE
Act	Pred.	Days	ES	EF	LS	LF	SLACK	SLACK
WM	-	2	0	2	2	4	2	0
WT	-	5	0	5	0	5	0	0
WDC	WM	3	2	5	4	7	2	0
WDR	WM,WT	2	5	7	5	7	0	0
WSS	WDC	4	5	9	7	11	2	2
WDN	WDR	4	7	11	7	11	0	0
WDP	WDR	5	7	12	8	13	1	1
WSI	WSS,WDN	2	11	13	11	13	0	0

Two columns have been added to this table to show total slack and free slack. Total slack is the difference between the time available and the time required to perform each activity. Using this definition, slack on activity WM is 2 (late finish of 4 minus the early start of 0) minus the duration of 2 for WM, i.e., 2. It can also be obtained by taking the difference LS – ES or LF – EF.

Free slack is the amount that an activity's completion can be delayed without delaying any of its immediate followers. For example, WSS with an EF of 9 is followed by WSI with an ES of 11. Therefore, WSS could be delayed up to 2 days with no impact on WSI. This information is useful when leveling resources or when asked to approve a slippage in an activity. If the slippage is less than the free slack, it will not delay any other activity.

ILLUSTRATION 17.9.4 Replanning.

The standard deviation for the critical path is a measure of the uncertainty associated with that activity or event. It permits the determination of the probability of completing the project on or before (or after) any specified time. For example, for the illustration network the standard deviation of the ending activity WSI is 1 day. Thus, it can be said that the probability of completing the project in 12 days or less is 16 percent. Similarly, the probability of completing the project in 14 days or less is 84 percent. The probability of completing in 15 days or less is 97.5 percent. The probability is nearly 100 percent that the project will be done in 16 days or less.

Such information can be of considerable value. If, for example, a major meeting is dependent on completing the project discussed in the illustrations, it might be desirable to schedule the meeting no earlier than the 17th day. In more complex projects, it is not uncommon for several paths to converge just prior to a meeting or other high-cost/high-visibility event. The more converging paths there are, the greater the probability that at least one of them will be late. Using some simple probability calculations, that probability can be calculated for alternative dates and the meeting scheduled accordingly.

There are serious deficiencies in the theory of PERT as originally developed, most notably that the uncertainty of an event is dependent on only the critical path leading to that event. To wit, as seen in Illustration 17.9.5, another path with 2 days of slack could result in a delay in completing the project with nearly the same probability as the critical path.

There are better ways to deal with this problem. Conceptually, it is similar to that obtained from reliability calculations. In reliability, the probability of a unit failing is the probability that at least one component of that unit will fail. In project management, the probability that an activity will be late is the probability that at least one of the paths leading to that activity will be late. Clearly, all other things being equal, the more components in a unit the greater the probability of failure. In a project, the more paths leading to an activity, the greater the probability that the activity will be late.

The best solution to this is to use one of the software packages that employ Monte Carlo simulation to more adequately develop the distribution of the ending activity or event by including the implications of all paths through the network. This can be augmented with the reliability type of calculations.

To perform the PERT calculations it is necessary to have the three time estimates: a, m, and b. Had they been estimated originally they would have resulted in the durations used above except now we change the name of the durations to "t_e" to reflect the new meaning of the "expected value." The calculations of early and late times are the same as before.

		Days								TOTAL		
Act.	Pred.	a	m	b	t_e	ES	EF	LS	LF	SLACK	σ	σ^2
WM	-	1	2	3	2	0	2	2	4	2	2/6	4/36
WT	-	3	5	7	5	0	5	0	5	0	4/6	16/36
WDC	WM	1	3	5	3	2	5	4	7	2	4/6	16/36
WDR	WM,WT	1	2	3	2	5	7	5	7	0	2/6	4/36
WSS	WDC	1	3	11	4	5	9	7	11	2	10/6	100/36
WDN	WDR	2	4	6	4	7	11	7	11	0	4/6	16/36
WDP	WDR	3	4	11	5	7	12	8	13	1	8/6	64/36
WSI	WSS, WDN	2	2	2	2	11	13	11	13	0	0/6	0/36

In addition, the standard deviation (σ) and variance (σ^2) are shown. Since, in PERT, the variance of the end event, or activity, depends only on the activities on the critical path, sum the variance of the activities with zero total slack to get 36/36, or 1.0 days2. Taking the square root of the variance, the standard deviation of the ending activity is 1.0 day. The probability of completing the project in 15 days, according to the PERT theory, is 97.5 percent.

It should be noted that the path WM-WDC-WSS-WSI has slack of 2 days. Yet it has a variance of 120/36 and therefore a standard deviation of 1.825 days. Thus, the probability of completing that path in 15 days is only a little better at 98.6 percent ($Z = (15 - 11)/ 1.825 = 2.19$). Thus, this path could be as, if not more, troublesome than the critical path.

ILLUSTRATION 17.9.5 PERT.

Monte Carlo Simulation. This technique is similar to PERT except for the computation procedure. The time computations are the same as in CPM except they are repeated many times, sampling from the distributions associated with each activity, and then the distributions for each activity's completion time is developed from the results. Thus, the uncertainties of all activities that precede a given event are considered in determining the uncertainty of that event. This is especially valuable knowledge when planning a project on which there is a substantial penalty for late completion. The Monte Carlo simulation provides a quantitative means for dealing with this problem.

Resource Management. Implicit in the preceding discussion has been the assumption that whatever quantity of resources are required in any given time period, they will be available. This is a tenuous assumption at best. Further, it is assumed that there is no limit on the number of resources that can be working on a given entity or in a given space at any one time. Such constraints can be incorporated in the network plan, but this is generally not a wise thing to do as it may unnecessarily constrain other possible solutions.

Until resources implications are considered, the calculations discussed to this point merely provide time frames within which activities *may* be scheduled. There are two general classes of problems in this area, time-constrained and resource-constrained scheduling. See Illustrations 17.9.6 and 17.9.7.

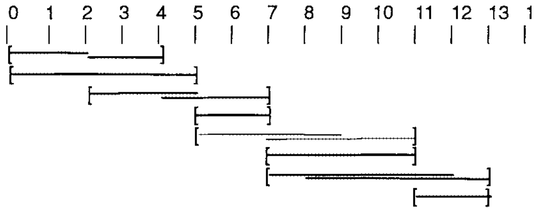
If time is of the essence and whatever resources required can be obtained, it is still desirable to bring the minimum necessary units of resource onto the project and avoid frequent hiring and firing. One experience by the author in using a program of this type resulted in a recommendation for the hiring of additional skilled tradespersons such as 25 die setters and 15 electricians. At the same time, based on historical approaches to the same problem, the personnel department was attempting to fill requisitions for 10 die setters and 20 electricians. After examining our analysis, a quick revision was made to the hiring plans to match the project scheduling software's recommendation. Thus, savings can be substantial both by avoiding overhiring and hiring in the wrong pattern, incurring the resulting delays of the project.

There are many software programs that can handle this problem, albeit with varying degrees of sophistication. Research has been conducted on scheduling projects using job shop scheduling rules similar to the research familiar to most industrial engineers reported by Conway, Maxwell, and Miller [16]. In general, similar conclusions have been reached by other

Resource leveling is accomplished with the aid of a Gantt chart. Each activity is plotted with an "open bracket" marking the early start and a "close bracket" marking the late finish. The activity duration is plotted to show both the early (top line) and late (bottom line) alternatives. The resources required are shown on the left with the number in parentheses showing the resource days R-D.

It is useful to develop the early and late resource profiles by adding the resources required on any specific day. For example, for the early profile on day 1, WM and WT each require 1 unit for a total of 2 units of resource. On day 8, WSS requires 3 units, WDN requires 1 unit and WDP requires 3 units for a total of 7 units. Similarly, when determining the requirements for the late profile on day 8, WSS requires 3 units and WDN requires 1 unit for a total of 4.

	Resources Req'd Units	R-D
WM	1	(2)
WT	1	(5)
WDC	2	(6)
WDR	4	(8)
WSS	3	(12)
WDN	1	(4)
WDP	3	(15)
WSI	1	(2)
		(54)



Day #	1	2	3	4	5	6	7	8	9	10	11	12	13	14
Early resource profile	2	2	3	3	3	7	7	7	7	4	4	4	1	54
Late resource profile	1	1	2	2	3	6	6	4	7	7	7	4	4	54
Average	4	4	4	4	4	4	4	4	4	4	4	4	4	52
Critical path	1	1	1	1	1	4	4	1	1	1	1	1	1	19
WM	1	1												2
WDP								3	3	3	3	3		15
WSS						3	3	3	3					12
WDC			2	2	2									6
Total	2	2	3	3	3	7	7	7	7	4	4	4	1	54

The average resource is determined by dividing the total resource-days required by the duration of the project, 13 days, to get 4 units per day. The critical path requirement is simply the resource requirements for those activities on the critical path. It makes sense to show those first because these activities cannot be moved without delaying the project completion. Below the critical path are shown those activities having slack. The sequence in which they are listed reflects the order in which the activities were considered for leveling. Activity WM was scheduled at its earliest time. Activity WDP was originally scheduled at its latest time . WSS and WDC were scheduled at their earliest times. When it became clear that 7 units were required on at least three days, WDP was moved forward one day to be in process on days 8 through 12, thus making the requirement for 7 units contiguous over 4 days. While there are other schedules which might be acceptable, this one has good characteristics in that it starts and ends with a small resource requirement and holds steady requirements of 3, 7 and 4 in between.

ILLUSTRATION 17.9.6 Time-constrained resource leveling.

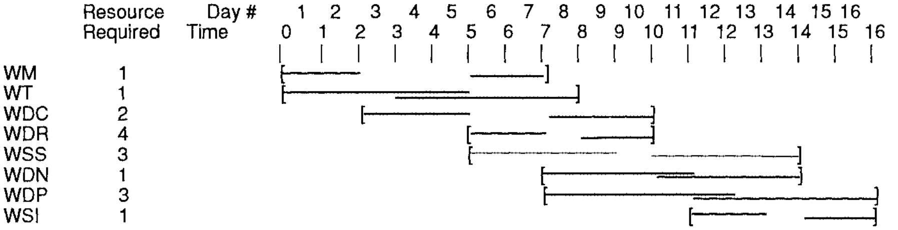
researchers [17,18]. Nevertheless, experienced project managers can improve on most schedules derived in this manner.

Similarly, there are many project scheduling software programs that can solve the resource-constrained scheduling problem. There are two basic approaches: (1) assign resources to activities in accordance with one or more of the job shop scheduling rules and letting the finish time for the project go where it may, and (2) perform successive iterations using the time-constrained resource leveling procedure, lengthening the time available for the project at each iteration. The latter is demonstrated in Illustration 17.9.6.

There are two types of resources that require different approaches to the problem. They can be characterized as homogeneous versus heterogeneous, common versus unique, or trade versus individual. The first of these, scheduling trades, assumes that all units of resource in a class have basically the same capabilities—a carpenter is a carpenter is a carpenter. Most scheduling packages available today are of this type.

The other type of program, for scheduling individuals, assumes that each individual has unique capabilities. The author recognized this in attempts to design software for scheduling draftspersons and engineers in an engineering/drafting operation. One engineer could do bumpers very efficiently but was very slow on quarter panels (fenders). Another had compa-

Resource constrained leveling proceeds in the same manner. In this case, the activities were scheduled in the sequence originally calculated, recognizing the limit of 4 units of resource per day. When that limit was reached, the next activity was delayed until resources were available. The project now requires 16 days.



	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	
Early resource profile	2	2	3	3	3	7	7	7	7	4	4	4	1	0	0	0	54
Late resource profile				1	1	2	2	2	6	6	4	7	7	7	4	4	54
Average	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	48
WM	1	1															2
WT	1	1	1	1	1												5
WDC			2	2	2												6
WDR						4	4										8
WSS								3	3	3	3						12
WDN								1	1	1	1						4
WDP												3	3	3	3	3	15
WSI												1	1				2
Total	2	2	3	3	3	4	4	4	4	4	4	4	4	3	3	3	54

ILLUSTRATION 17.9.7 Resource-constrained scheduling.

rable abilities of another mix. For lack of a better term, this was dubbed the *drafting room scheduling problem.* It can be characterized as a 3D assignment problem, where the resources and the activities form the usual dimensions but the problem is compounded in that neither the jobs nor the resources are available at the same instance that resources are assigned. Currently, it is unclear that this problem has been solved in commercially available software.

A similar problem occurs in many architect offices and software shops where each person is assigned several activities and works on more than one at a time. Thus, the software program should be able to monitor the hours allocated to each activity and the total commitment of the individual's time. Several packages have been developed to handle this problem; however, they tend to be tailored to the particular profession as opposed to being more general purpose.

While there have been analytical solutions proposed for these problems, the analytical solutions tend to be limited to small problems of little practical significance. It is expected that expert systems concepts and even artificial intelligence will provide a new class of solutions for these problems.

CPPS—Time-Cost Trade-off. This was the technique that was developed as a result of the pioneering effort by Kelley (at Sperry Univac) and Walker (at DuPont) concurrent with the development of PERT [19,20]. The original solution technique was linear programming and therefore the capacity was severely limited at the time. The problem, as originally characterized, was to determine the optimum project duration given that each activity in the network could be performed in a range of durations, one of which was least costly. This was desirable because (once a new process plant was authorized to be built or existing plant shut down for maintenance) every day the plant was not available a loss was incurred due to the inability to sell the product that it might have produced. The problem is akin to the classic inventory problem where one cost—carrying cost—decreases with smaller order quantities while another cost—ordering cost—increases. On the project, there may be opportunity costs (product that could have been sold if it had been available) or interest costs (on the construction loan) that decrease with shorter project duration while other costs of performing the project increase with shorter project duration. The objective is to determine the project duration for which the sum of these costs is the least, as shown in Illustration 17.9.8.

To perform the crash calculations, two additional items of information are required for each activity, the crash cost and the number of days the activity can be crashed. The crash cost is the slope of the time-cost curve. Thus to reduce the project time in the least costly manner, it is necessary to reduce the durations of activities on the critical path and, later activities which were not originally on the critical path, crashing first those activities with the least slope or cost per day.

Act.	Pred.	Crash Cost ($/Day)	Crash Days	Normal Days	ES	EF	LS	LF	TOTAL SLACK
WM	-			2	0	2	2	4	2
WT	-	$100	2	5	0	5	0	5	0
WDC	WM	$ 75	1	3	2	5	4	7	2
WDR	WM,WT	$125	1	2	5	7	5	7	0
WSS	WDC	$ 50	1	4	5	9	7	11	2
WDN	WDR	$ 50	1	4	7	11	7	11	0
WDP	WDR	$ 80	2	5	7	12	8	13	1
WSI	WSS,WDN	$150	1	2	11	13	11	13	0

This is most easily accomplished by setting up the following table.

Paths			Crash Activity	Cost	Total Additional Cost
WT,WDR,WDN,WSI	WT,WDR,WDP	WM,WDC,WSS,WSI			
13 days	12 days	11days			
12 "	12 "	11 "	WDN	$ 50	$ 50
11 "	11 "	11 "	WT	$ 100	$ 150
10 "	10 "	10 "	WT & WSS	$ 150	$ 300
9 "	9 "	9 "	WDR & WDC	$ 200	$ 500

WDN is crashed first as it is the least costly activity on the critical path. This makes the first two paths equal in length at 12 days. WT is next as it is in each of these paths but is less costly than WDR. Now all paths are equal in length requiring that combinations of activities be crashed. WT and WSS combined have the lowest cost of $150. WDR and WDC are next at $200. The cost column gives the slope of the total cost curve for the project which can be weighed against the savings which might accrue for having completed the project earlier. For example, if the savings expected from implementing this project are $125 per day, there would be a net saving of $ 100 by performing the project in 11 days instead of 13. The important comparison , however, is the marginal cost. While there would be savings from performing the project in 10 days, it would only be $ 75. The marginal cost of the 10th day is $150 versus a savings of $125 resulting in a net marginal cost of $ 25.

This process can get very complex quickly but can be used on most projects to get considerable reduction of time with no more formal procedure than that shown above. For a more robust procedure, there are a few project management scheduling packages which incorporate this feature.

ILLUSTRATION 17.9.8 Time/cost trade-off (CPPS).

To illustrate, consider only the activities on the critical path in our example problem. To shorten the time for the project, the duration of the critical path must be reduced. It is realistic in practice to analyze the critical activities because there will generally be only one or a few paths that require significantly more time than all the rest. These may consist of as few as 10 percent or less of the activities in the network. Further, some of these may not be amenable to time reduction while others may be very simple to reduce. For example, on a project to design a new engineering releasing system, a substantial reduction in negative slack was achieved when it was recognized that all interchange of documents was planned as activities handled through intracompany mail, each requiring 3 days. Those intracompany mail activities with negative slack were changed to hand carry delivery, reducing the project duration by some 100 days.

While the author is unaware of any commercially available software for performing these calculations, the concept should be applied manually in all project planning and scheduling to achieve the lowest overall cost of the project.

Cost Management. Earned value analysis is the modern concept of what was originally known as PERT/cost, a system that was touted in the early 1950s but which was found to be too rigid in practice. Earned value is primarily a client-oriented cost control system in that it aids in ensuring that the client pays only for work that is done and materials actually delivered. It essentially recognizes costs at the time when the check is drawn to pay for the work or materials.

Earned value is very similar in concept to a standard cost approach for volume production operations, permitting analyses of cost differences due to schedule variance and spending variance. Because project work is essentially performed one time, the measurements must be compared to estimated costs for each activity or work package.

Earned value analysis has three major cost measurements: budgeted cost of work scheduled (BCWS), budgeted cost of work performed (BCWP), and actual cost of work performed (ACWP). These are measured at the activity or work package level and summed progressively through the work breakdown structure to provide an overall measure for the project as a whole. Thus, managerial analysis can begin by determining if there is a problem for the project and progress downward through the WBS to determine the contributing causes of a problem.

Cost management begins with a budget that, when approved, becomes the baseline for all further control. The first measure for an activity, group of activities, or the project as a whole is the BCWS. It is the amount that should have been expended for work scheduled during the reporting period. It is accumulated for prior periods to obtain the amount that should have been expended to the reporting date. The cumulative cost curve to the end of the project is generally in the shape of an *S* and is called the S curve. (See Illustration 17.9.9.)

Not all work is performed to schedule, so the next measure is BCWP. This indicates the number of dollars that should have been expended during the reporting period, or cumula-

For cost management purposes, consider the schedule developed in the time-constrained resource illustration as the official baseline schedule. Consider the cost of the resource to be $100 per day and the zeros will be dropped for convenience

Day #		1	2	3	4	5	6	7	8	9	10	11	12	13	14
Time	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14
WM		1	1												
WT		1	1	1	1	1									
WDC					2	2	2								
WDR							4	4							
WSS							3	3	3	3					
WDN									1	1	1	1			
WDP									3	3	3	3	3		
WSI													1	1	
Total Budgeted		2	2	3	3	3	7	7	7	7	4	4	1	54	
Cumulative Cost (In $100)		2	4	7	10	13	20	27	34	41	45	49	53	54	
Revised Budgeted		2	2	1	3	3	9	_							
Revised Cumulative Cost		2	4	5	8	11	20	_							
Actual Costs Incurred		2	3	4	4										
Cumulative Actual Cost		2	5	9	13										

If time now is at the end of Day 4, the BCWS is $700. Assuming that activity WDC did not get started until Day 4, the revised schedule shows it still taking 3 days. The revised cumulative cost now shows the BCWP to be $800, a schedule variance of $200 underspent. If the actual costs are as shown by period, the ACWP is $1300, a spending variance of $500 overspent. Thus, this project is, to date, in trouble on both schedule and spending.

A forecast for the remaining activities would be necessary to project accurately into the final completion date and cost. WDC had slack of 1 day so its delay should not affect the completion date. Only detailed knowledge of the causes of the cost overrun can aid in determining future costs. In the absence of such understanding, however, two assumptions are possible. First, it can be assumed that there will be no further overruns, in which case the EAC cost could be forecast as $5,900 ($5,400 + $500 variance to date). The second assumption might be that the remaining 8 days will incur cost overruns at the same rate, i.e., $125 per day ($500 / 4 days), in which case the EAC would be $6,900 ($5,400 + $500 + 8 X $125).

ILLUSTRATION 17.9.9 Cost management.

tively to the reporting date, in performing the work that was actually performed. The difference between BCWS and BCWP is a measure of *schedule* variance, comparable to the *volume* variance in a standard cost system.

The work that is performed may not cost exactly what it was estimated to have cost. Thus, the third measure is ACWP. The difference between BCWP and ACWP is a measure of the *spending* variance, comparable to the *rate* variance in the standard cost system.

From these measures the competent project manager can determine if actual expenditures are basically consistent with the actual progress on the project and determine what, if anything, can be done about it. Because of the pyramidal structure of the accounting system built into the project management software, a variance at the project level can be traced through the many levels of detail to the specific activity(ies) contributing to the problem. It focuses the attention of the project manager on those areas most in need of diagnoses and direction.

Using various methods, based on different assumptions, a projection can be made of the estimate at completion (EAC) cost. The estimated completion date is more accurately projected based on the time-schedule calculations.

The earned value approach has been adopted by the Department of Defense (DoD), National Aeronautics and Space Administration (NASA), Department of Energy (DOE), and other federal agencies. The DoD version is called Cost/Schedule Control Systems Criteria (C/SCSC) and is well documented in Fleming [11]. Contractors performing work for these agencies may be required to maintain cost and schedule records and controls, and report findings in accordance with C/SCSC. It should be noted that certification of compliance with C/SCSC is based on the contractor's total management system of which a part may be a standard project management schedule and cost system. While the software vendor's package is not certified as such, it may be appropriate to determine if the package has been an integral part of a C/SCSC certified contractor's management system.

Two techniques developed in the early 1960s offer capabilities not found in the more familiar project management software packages. Because of the additional logic available in these, it is expected that they will become more popular as more deliberate strategic planning of projects develops, and even more popular as project management concepts are used in corporate strategic planning.

Decision CPM (DCPM). The techniques discussed in the previous sections have some constraints that limit their flexibility in practical application. For example, there is no provision for identifying alternative methods of performing the same task or meeting the same requirement. The only way to accomplish this is to incorporate one alternative in plan A and the other in plan B. If the number of alternatives is appreciably greater than 2 and there is interaction between alternatives, the task of evaluating these can be formidable.

DCPM, a concept first published in 1967 [21] allows alternative task sets to be defined, that is, mutually exclusive alternative methods for performing the task, one of which is ultimately to be selected. A task set is preceded by a decision node. The author is not currently aware of any commercially available software for solving this type of problem. For more details on this technique see either Weist and Levy [22] or Moder, Phillips, and Davis [23].

Graphical Evaluation and Review Technique (GERT). GERT could be considered an extension of DCPM with the addition of loops in the network (handy in portraying rework or cut-and-try development, for example) and more versatility in the decision nodes. Like DCPM, the author is not aware of any commercial software for this technique. GERT is discussed in Weist and Levy [22] and Moder, Phillips, and Davis [23].

Other Project Techniques

Work Breakdown Structure. One of the most fundamental tools in project management is the work breakdown structure (WBS). It is the tool by which a project, no matter how large, is subdivided into progressively smaller and smaller elements until the degree of detail is compatible with the needs of planning the work of the project.

A WBS is very similar to an assembly bill of materials. The emphasis is on deliverables such as a layout of a product, a detail design of a component, or a manufacturing instruction. There should be no attempt to portray the sequential relationships between the elements in a WBS. That is done later in the development of the network diagram. The WBS identifies the work content of the project, the work for which the contractor is to be paid. The approved scope statement, including the WBS, becomes the baseline against which technical and cost performances are measured.

The WBS is an important tool in controlling the work content of the project. All work that is required by the scope statement in the contract for the project must be identified in the WBS. Conversely, no work should be included unless it is in the scope statement. This then becomes the baseline for controlling changes to the scope and negotiating for appropriate budget or charges. Not only is this important to ensure proper recognition of the costs for any changes and appropriate charges to the client, it is vital in managing the project.

The WBS is also important in clearly establishing the strategy of the project. The manner in which the project is subdivided determines what problems will have to be dealt with by the project manager as well as each lower level member of the project team. Problems that are clearly within the responsibility assigned to the person responsible for a WBS element should be solved by that person. Problems that span two or more WBS elements require the involvement of the person who is responsible for all of those elements. One of the most important tasks of the project manager is managing the interfaces between WBS elements.

It is the author's opinion that the WBS should be tailored to the needs of the project. Its form should generally not be dictated by other needs of the organization, such as uniform cost collection across projects. For example, the U.S. Department of Defense requires level 1 to be by specific deliverables to ensure comparability of like elements across programs and vendors.

There are some basic principles that must be followed in developing a WBS including

- *Uniqueness.* A unit of work should appear at one, and only one, place in the WBS.
- *Summative.* The work content of a WBS element is the sum of the WBS elements immediately below and related to that WBS element.
- *Unity of responsibility.* A WBS element is the responsibility of one, and only one, individual.
- *Consistency.* The WBS must be consistent with the way in which the work is actually going to be performed, that is, it should serve the project team first and other purposes only if practicable.
- *Motivation by involvement.* Project team members should be involved in developing the WBS (as well as the network plan) not only to ensure consistency, but moreso to ensure buy-in to the project plan.
- *Documentation.* Each WBS element must be documented to ensure accurate understanding of the scope of work included, and not included, in that element.
- *Flexibility.* The WBS must be a flexible tool to accommodate the changes that are inevitable in a project while properly maintaining control of the work content in the project as per the scope statement in the contract.

Careful attention to developing a WBS according to these principles will reward the project manager and the organization with many benefits throughout the project.

Gantt Chart. The Gantt chart was developed by Henry Gantt about 1917 as a means for scheduling work in a job shop. It has become the most easily understood portrayal of a scheduled plan for a variety of types of work (see Fig. 17.9.5). While it was used extensively prior to computer methods for scheduling projects, it was often demeaned by the comment, "It conceals more than it reveals." Manual means for preparing Gantt charts were so time-consuming and expensive as to be practically "cast in bronze." As a result, the tendency was to delay redrawing them until the project was well off schedule.

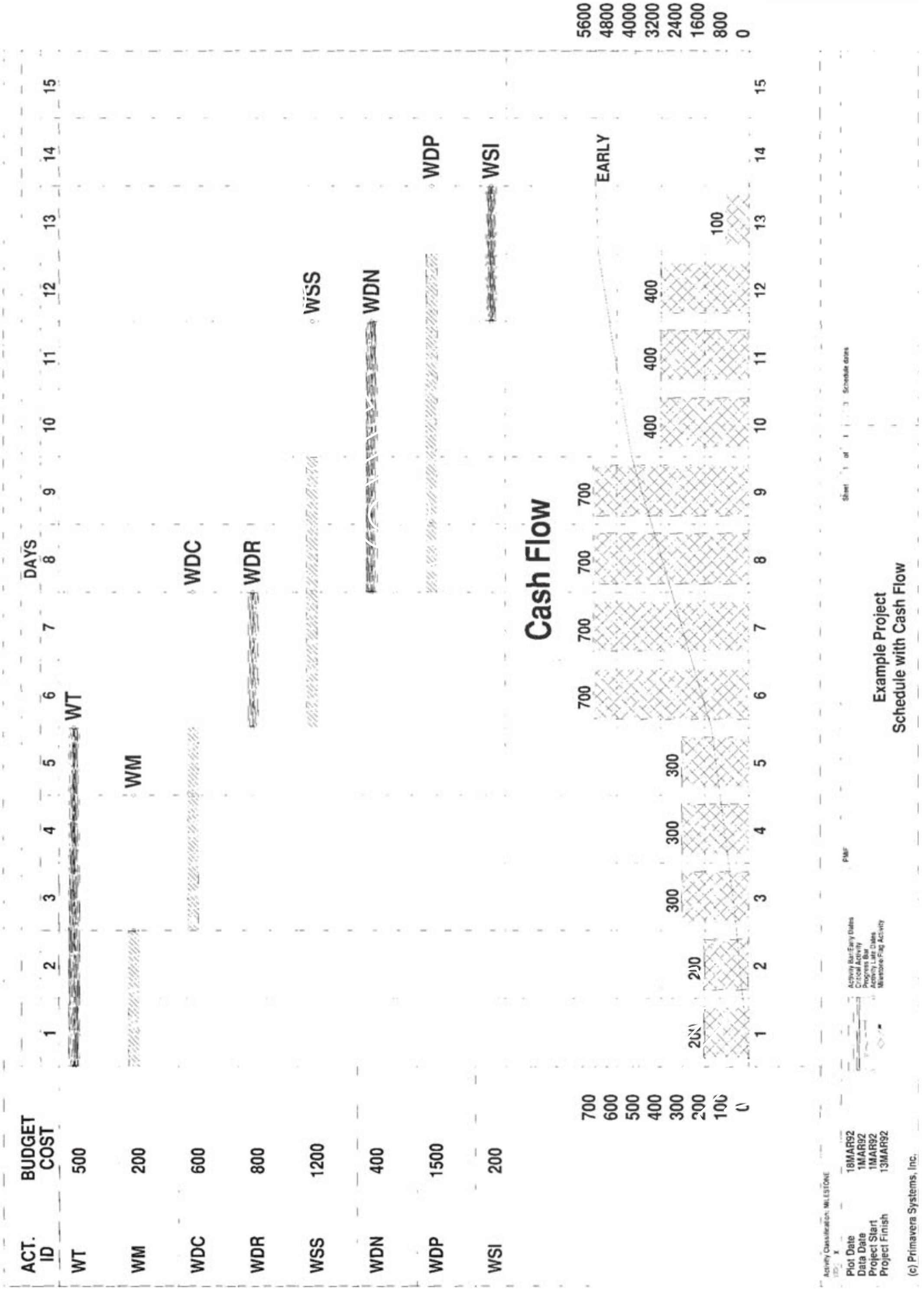


FIGURE 17.9.5 Gantt chart.

MPM software programs prepare Gantt charts rapidly and inexpensively with a wide variety of graphical formats. They are effective for communicating with clients, executives, middle managers, and line managers. Indeed, they are preferred by line managers who generally want to know what they are supposed to do and when.

Gantt charts do have deficiencies. They typically do not show the relationship between activities in the network. A special version, the connected Gantt chart, overcomes this but in so doing becomes more complicated. In general, it is best to use the simple Gantt chart for most purposes, bringing out the connected version or even the network diagram for more complex problem solving.

OPPORTUNITIES AND CAVEATS

Opportunities

Project management is the management of change. Change is increasingly the norm in business, industry, and government. The efficient management of change is essential to survival and MPM is the way to achieve that efficiency.

Many organizations that operate primarily in the project mode have adapted MPM as a way of life. An excellent example of this is the AT&T Business Communication Systems Division (now Lucent Technologies) that equips project managers with laptop computers loaded with a standard set of software useful in managing projects [24]. MPM was used in the construction of the English Channel Tunnel [25] and in developing new pharmaceuticals [26]. It was used in developing high-energy physics research capabilities at Sandia Laboratories [27] and on the Super Conducting Supercollider [28]. It was used to get new products to the market more quickly and to manage the Voyager II trip to Neptune [29]. It is even used in running the Olympic Winter and Pan American Summer Games [30].

MPM is becoming more popular for managers having responsibility for many small projects to simply keep track of their status and to understand the implications of both budget and resource availability. It is in this area that MPM offers one of the greatest opportunities for industrial engineers to contribute to the success of their organization. MPM can, and should, be applied at the plant level to manage all of the non-volume-production work being performed in the plant. It should then be expanded, where appropriate, to include all such project activity in a multiplant organization. The author had such an application working long before either time-sharing or microcomputer approaches to project management were available. Other than the slow turnaround, it was well received. It included personnel studies as well as new product and facility preparations.

Lest the examples cited in this chapter lead to any false impressions, MPM is applicable to all sizes of projects. The author has consulted on projects of all sizes and consistently uses the concepts whether building a house or performing small projects leading to the eventual completion of the house. Indeed, a standard recommendation to those new to MPM is to try it on do-it-yourself projects at home so that you will understand some of the detail before applying it at work.

Caveats

Care must be taken in applying MPM in an organization not familiar with its application. It can drive a project team too hard and develop resistance. One plant manager favored allowing supervisors to spend all the money provided in work orders rather than risk having to return to corporate unspent funds resulting from better project management. Care must be taken to ensure that benefits being enjoyed today are not lost with the introduction of new management tools.

Managers must understand that MPM tools are more precise than previous tools. They cannot be used in the same manner as the tools of the past. If they are misused, project team members will ensure that they are not accurate. If used properly, they can support effective team building and lead to projects being completed in conformance with technical requirements, on time and, often, under budget.

One of the ways in which these tools can be misused is to put too much pressure on the team members to perform. People who are pushed to extreme will avoid using the system if at all possible.

Finally, care must be exercised in using the tools to ensure the most appropriate means are used to improve performance. Following is a list, in a preferred sequence based on a general concept of the cost-benefit ratios, of ways to improve performance on projects [31].

1. *Expressing managerial attention and involvement* to show interest and concern, but not to the point of interfering with those who have to accomplish the tasks.
2. *Expediting* ensures that obstacles to progress are removed and resources are available when required.
3. *Improving methods* can reduce the work content, time required to complete a task, the resources used, and the resources wasted.
4. *Reassigning resources* can move the most efficient resources to the activities that are most critical.
5. *Reallocating resources* can move resources from noncritical activities, stretching their duration, to critical activities, shortening their duration.
6. *Overlapping activities* can allow work to proceed more quickly but with some risk unless extra attention is given to adequacy of communications and coordination.
7. *Defining activities in greater detail* can subdivide the work so more people can work on the project simultaneously.
8. *Deleting certain activities* is often feasible after careful review with the client of what is really essential.
9. *Changing the technology* applied is similar to methods improvement but may be more risky if it is a technology that is unfamiliar to the performing organization.
10. *Subcontracting or buying* the goods or services can often result in economies as well as timesavings, but with some loss in control and dependability.
11. *Applying additional resources* using the CPPS approach to time-cost trade-off can reduce the total time required, but note that this is 11th in this list.
12. *Changing target dates* on the total project, still delivering essential parts of the project at dates acceptable to the client, can minimize perceived poor performance.
13. *Changing the scope* of the project can permit timely delivery of essential elements and possibly avoid major failure of the project as originally conceived.
14. *Changing the person responsible* often results in major delays while the new person becomes acquainted with the project and the team, *and* the team gets acquainted with the new person.
15. *Changing the management information system* can lead to better performance but generally only after all participants have an opportunity to become familiar with it and it is adjusted to the peculiar needs of the organization.
16. *Changing the organization structure* often seems to be a quick fix but often it takes considerable time for the project team members to begin to function as a team.

MPM is not a panacea, but used wisely it offers many opportunities for improving the performance of an organization's project work and, as a result, leads to better performance in other parts of the organization because projects are more likely to be completed on time and under budget.

SUMMARY

Project management has grown from an early conception that it was simply planning and scheduling, then to include cost management, and now to a comprehensive responsibility for seeing that all aspects of the project are carefully integrated and managed. One view of this progression is that the early focus on scheduling and cost management solved a major problem at the time—inadequate control of time and cost. The success in dealing with these two vital areas has substantially reduced the time required and improved the accuracy and utility of these functions, making more time available to manage the other elements required for project success.

Project management experience has become recognized as one of the very important career steps on the ladder to general management. The project manager is the general manager of that project. The normal progression for successful project managers is on to larger, more challenging assignments.

The progressive industrial engineer can bring substantial benefits to an organization through project management. Purchase an inexpensive project management software package. Start with a small project in the department. Move to a larger project with another department that is receptive to change. By this time you should have a much better idea of what is required in project management software for your organization. Then move up to a still larger project involving several departments. By this time, the experience gained and the successes recorded should build the acceptance to apply these concepts plantwide, if not corporatewide.

If you choose to lead the implementation of MPM in your organization, take time to read more on the subject. PMI is publishing a growing body of literature and has available through its bookstore the most current literature. *Project Management: Strategic Design and Implementation* [32] should be especially helpful.

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FURTHER READING AND PROJECT MANAGEMENT SOFTWARE

The body of literature on project management increased substantially during the 1990s and the availability of software (both in terms of vendors and software capabilities) changes every year. One current source for references to this literature and current software information is the Project Management Institute (Four Campus Boulevard, Newtown Square, PA 19073-3299 USA. Telephone: +610-356-4600, fax: +610-356-4647, e-mail: pmihg@pmi.org).

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BIOGRAPHY

Francis M. Webster, Jr., is retired editor in chief of the Project Management Institute. He has received PMI's Outstanding Contribution and Person of the Year awards and was elected a PMI Fellow in 1991. He created the *PMNETwork* (the professional magazine of PMI), was responsible for the *PMI Software Survey* for eight years, has led workshops at PMI annual meetings, and wrote the questions for two sections of the first PMP exam. He has had a successful career in engineering at Phillips Petroleum Company, in management including manager of operations research at Chrysler Corporation, and as a university professor, retiring from Western Carolina University as Professor Emeritus in 1992. He has consulted on the management of projects and developed four project-scheduling packages. He earned a B.S. in chemical engineering from the University of Missouri in 1952, an M.S. in industrial administration from Carnegie Mellon University in 1958, and a Ph.D. in production management from Michigan State University in 1978. He has recently published *PM 101 According to the Olde Curmudgeon,* which will be followed shortly by PM 102, available through the Project Management Institute.

CHAPTER 17.10

CASE STUDY: APPLYING LEARNING CURVES IN AIRCRAFT PRODUCTION—PROCEDURES AND EXPERIENCES

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Learning curves are used in aircraft production to estimate, budget, and control levels of resource and to assess contract performance. Learning is an empirical relationship, and as such the engineer or analyst must learn to recognize and deal with the practical problems of data analysis and modeling, including the exploitation of basic learning curve properties. This chapter will discuss the use of alternative forms of the learning relationship, principally the unit and cumulative average learning curves, and illustrate how these can be used to good effect within a manufacturing company. This chapter also demonstrates how it is possible to segment learning curves into discrete elements to model the effects of variations in specific cost drivers. Examples and techniques are discussed.

BACKGROUND AND SITUATION ANALYSIS

Introduction

The precise nature and cause of the learning phenomenon is not fully understood. As a consequence there are differences of opinion and interpretation across the industries that experience it. This case study illustrates an approach adopted by BAE SYSTEMS, and offers a route by which to quantify the issues propounded by Richard Engwall in Chap. 17.5. There are other approaches that are equally valid.

Definition of Learning

Learning can be defined [1] as "*the process by which an individual acquires skill and proficiency at a task, which in turn has the effect of permitting increased productivity in his or her performance of that task.*"

The cumulative effect within an organization of several individuals' learning could be considered to be that organization's learning. Northrop's definition of organizational learning [2] from the early 1960s states: "*A learning curve is the rate at which management identifies and solves problems in relation to design, methods, shortage of parts, inspection, and shop education.*"

Neither definition excludes the other; indeed one is an enabler or driver to the other. It is around a combination of these definitions that this case study is based.

In some ways it is fitting that some 32 years after the Wright brothers' pioneering first flight that another Wright [3] should pioneer the use of the learning phenomenon in forecasting the cost of aircraft manufacturing. Wright observed that the cumulative average labor hours followed a learning relationship, but many other authors have also mooted and applied learning to the unit labor-hour costs. Whichever model is used, it must be remembered that learning is an empirical relationship (i.e., based on observations, not mere theory).

Unit or Cumulative Average Learning: The Choice

While the cumulative average learning relationship has the benefit of its smoothing property [4] over the unit version, this same property does have the drawback of amortizing the cost of common and peculiar elements of work over the production run, as illustrated in Fig. 17.10.1. Consequently, where there is a high degree of peculiar work content, the cumulative average version has the tendency to disguise and amortize the true learning effects.

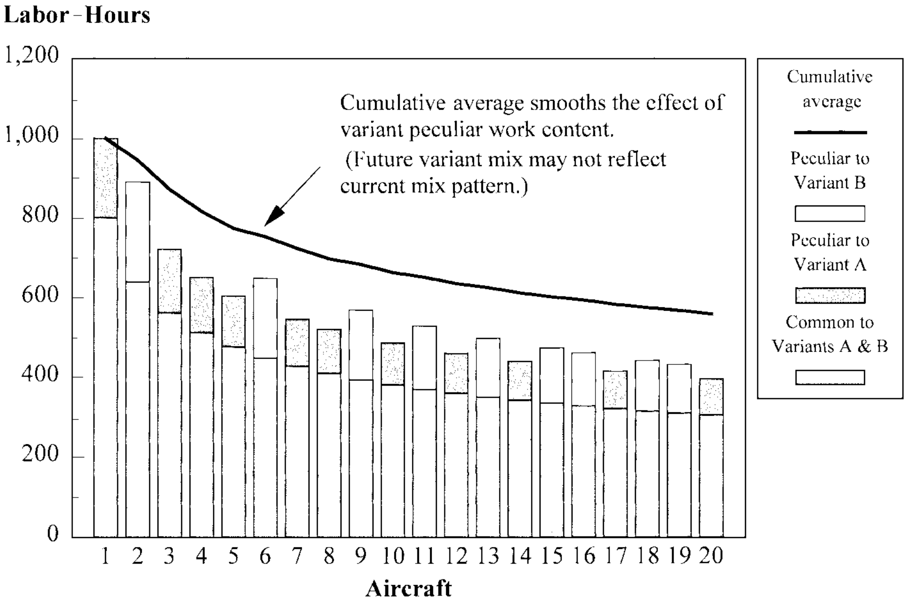

FIGURE 17.10.1 Disadvantage of cumulative average smoothing.

For the analysis of similar units (low peculiar work content), the two relationships are effectively interchangeable. In some respects, data might be more easily fitted by considering the cumulative average version of this curve, as only batch or lot totals are required, not individual cumulative average values. Whichever model is chosen, it must reflect the circumstances (in the widest sense) in which it is going to be applied. Learning is not a tool for the industrial historian, but rather for the engineer who wants to use it to imply knowledge or expectation about some future event, hopefully with the intention of influencing it.

Drivers of Learning Within Aerospace

In order to influence learning, an organization needs to have some understanding of what enables or inhibits learning in either a generic sense, or in the context of its own operating practices. This is not as easy as it sounds; learning is described as a complex subject influenced by a number of factors [1]. Numerous writers have observed and substantiated that learning is not solely the result of operator experience and/or motivation, but is dependent also on the engineering investment and operational conditions and constraints [4].

Jefferson [2] expresses the view that learning is the net effect of several factors, and cites the experience of Northrop in quantifying the principal enablers of learning (Fig. 17.10.2). Unfortunately, the supporting evidence is not provided, so the reader is left to speculate on its value and its interpretation in a wider or alternative environment.

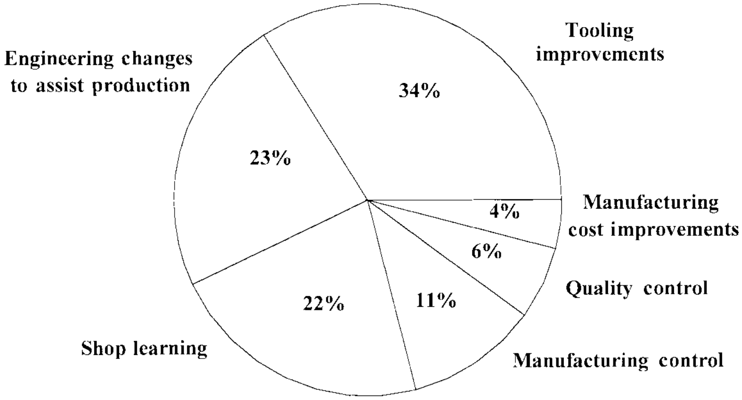

FIGURE 17.10.2 The constituent elements of production learning. (*Source: P Jefferson, "Productivity Comparisons with the USA—where do we differ?,"* Aeronautical Journal, *Vol. 85 No. 844, May 1981, p. 179.*)

However, as no two organizations are alike, there are probably no universal values; Jacobs [5] postulates that "*cost is the final measure of everyone's inefficiencies.*" Smith [6] observes that different learning rates exist between similar products at different locations, and accepts that this is the influence of causal factors.

If learning is so difficult to predict accurately, or understand, does it really matter? It is a question of degree. It is not necessary—and probably not possible—to understand every nuance of the learning curve. Learning is an empirical relationship, not a mathematical axiom; it can provide an estimate, not a precise measurement. However, it is necessary that an organization understands the major causes and drivers of learning that it experiences. Failure to do so may result in reduced profits or lost business. An error of 1 percent in the rate of learning assumed aggregates to a cumulative error of 6 percent over 100 units and 10 percent over 1000.

Learning: Where Does It End?

Does learning continue indefinitely, or does it have a finite limit? If it does, where or when does this occur? These are issues which have been much debated across negotiating tables and in the pages of respected journals for many years—and probably will continue to be for many more.

To allow for concerns about the perpetuity of learning, a variation of the unit learning curve is that of a finite learning model, which assumes that learning will reach a saturation point. There is documented support [7] for the finite learning model, in which it is assumed that there is an incompressible lower limit to the learning phenomenon.

Although intuitively this has some appeal, its major drawback in practice is that it requires either a nonlinear technique to calibrate the model from actual data, or a supposition about the saturation level. (Even a standard time value is not necessarily a practical assumption, as the engineering definition and solution are likely to be modified in order to achieve productivity improvement targets inherent in the learning function.)

Harvey [8] reflects also on the tendency for learning to flatten after about 100 units within the U.K. aircraft industry, but does recognize also that this is not necessarily acceptable, affirming the need for continuous learning in response to market drivers. He considers also the argument of continuous and saturated learning as being somewhat academic [9], as wartime experience in the United States showed continuity of learning into tens of thousands of units. It could be countered, somewhat cynically perhaps, that this is just a measure of how inefficient it can be at the onset of a crisis situation such as war, and that the continuing need drove the improvement!

Protagonists of the finite learning argument observe that learning often flattens off before the end of a production run. This is not merely a linear perspective of an exponential function, but one that can be illustrated by a log-log plot also. The real question is not does it occur, but why and when?

OBJECTIVES AND SCOPE

The primary objective of this case study was to identify a framework in which to assess the impact on learning of a variety of business scenarios in recurring production aircraft activities. The framework was required to be both practical and flexible, and capable of being used for both data analysis and forecasting at a high level. It was not the intention to provide a tool for detailed cause-and-effect analysis at the operational level, as the reaction time over an aircraft build stage was considered to be too slow to be of benefit at that level. It is far better to prevent a problem than to have to cure one.

The scope of the study was to be limited initially to assembly data, as this represented the area in which traditionally more marked learning rates are observed. However, consideration of learning in other areas was not to be excluded specifically.

The suitability of the proposed framework was to be demonstrated by addressing three specific issues:

- Does the rate of production have a significant impact on the rate of learning?
- How can the disruptive effects of work transfers and breaks in production be quantified in advance, or even be controlled?
- Why is learning often observed to truncate significantly before the end of production? Does learning have a saturation level?

ORGANIZATION OF THE PROJECT

The project called for the following four distinct phases or activities to be performed.

Literature Search

It is always good practice to review the work of others. No one person or organization has a monopoly of good ideas, knowledge, or experience. Lessons learned or observed by others can help to direct another's thinking or to avert nugatory work. The major benefit is that it highlights the areas of common knowledge and substantiation to date, and underlines the areas of ignorance or supposition. The difficulty is finding the existing research that is relevant to the case study.

Choice of Model

A number of mathematical models on learning have been developed, as the literature search highlights. The one chosen had to satisfy two basic criteria:

- It had to be flexible enough to be used to model the resource requirements implicit in alternative business scenarios.
- It had to be simple enough to be in a format that could be used with any standard data analysis package available to engineers in an office environment.

It was in this phase where the various hypotheses would be developed and a generic model compiled.

Data Sampling and Regression Analysis

This phase required the use of standard data analysis techniques such as linear regression and correlation. Actual data was to be gathered relating to the observed labor hours and the hypothesis or event to be tested. In some respects, this phase would prove to be the most challenging; labor-hour data was readily available, because of the requirements placed on defense contractors to maintain records, but historical records of other types are not always available. This would either limit the range of scenarios that could be tested, or require the use of estimated data. In terms of the results documented in this case study, the former applies.

Involvement

Unless an organization is quite small, it is unlikely that any one person will be able to postulate and understand all the drivers of learning for that organization. It is important that others be involved during the process:

- Those who are involved in the product delivery to identify the obstacles and constraints to efficiency
- Those who can stand back and take a wider perspective and draw links to wider business issues

Discussions with such subject matter experts are essential before and after the data analysis stage in order to test the sensibility of the analysis, and to gain acceptance of the results.

PROCEDURE AND APPLICATION OF TOOLS

Choice of Model: Alternative Forms of the Learning Curve and Their Applications

In selecting the appropriate learning model it was recognized that there were alternatives and variations to the cumulative average and unit learning versions that needed to be considered.

Finite Learning Model (Saturated Learning). In its simplest form, this can be expressed as a variation on the unit learning curve:

$$M_A = M_S + M_V A^{\tau}$$

where M_A = labor-hour value at Unit A
M_V = variable labor-hour value of the first unit
M_S = labor-hour learning saturation level
τ = the learning exponent, defined by the relationship
$\tau = \log(p)/\log(2)$

with p being the learning percentage expressed as a decimal (e.g., 80% = > 0.8).

$$M_1 = M_S + M_V = \text{total labor-hour value of the first unit}$$

As an alternative to the finite learning model, it is common practice to utilize breakpoints (Fig. 17.10.3) to represent a change in the rate of learning.

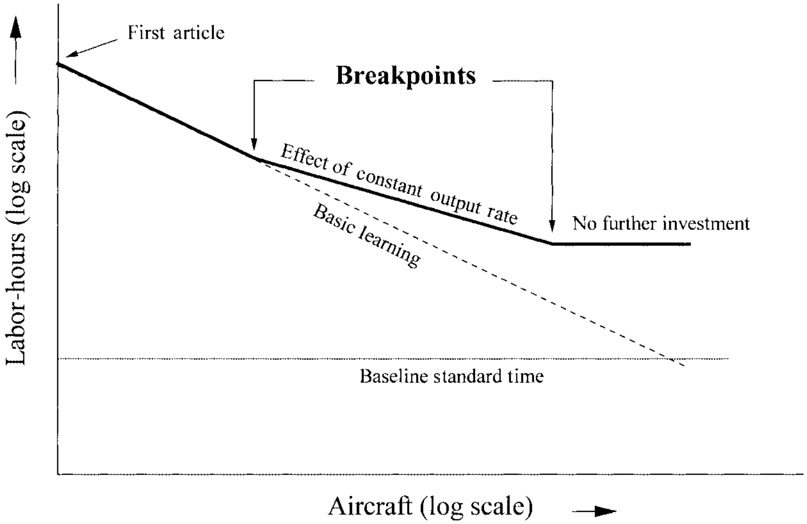

FIGURE 17.10.3 Example of learning curve breakpoints.

Modeling Discontinuities in Learning. Observation of numerous tasks which exhibit learning characteristics reveal that the phenomenon of breakpoints does appear to occur. The impact of a breakpoint can be reflected mathematically:

$$M_A = M_1 A^{\tau} \qquad \text{for } A \le B$$

$$M_A = M_1 B^{\tau-\sigma} A^{\sigma} \qquad \text{for } A \ge B$$

where M_A = Labor-hours at unit A
M_1 = Labor-hours at first unit
B = Point at which the breakpoint is assumed to occur
τ = Learning exponent before the breakpoint
σ = Learning exponent after the breakpoint

The main benefit of this model over the finite learning model is that it can reflect the saturation condition, while still being in a form that can be transformed into a linear model for analysis:

$$M_A = M_1 X^{\tau} Y^{\sigma}$$

such that

$$X = A \text{ for } A \le B$$

$$Y = 1 \text{ for } A \le B$$

$$X = B \text{ for A} \ge B$$

$$Y = \frac{A}{B} \text{ for } A \ge B$$

A linear transformation of this simplified model allows a multilinear regression to be performed:

$$\log(M_A) = \log(M_1) + \tau \log(\mathrm{X}) + \sigma \log(\mathrm{Y})$$

Segmenting the Learning Curve—The Concept of Cost Drivers

However, accepting the observation of multiple drivers as being valid in principle, if it were possible to express the cumulative effect of each driver in relation to the cumulative quantity produced, it suggests that it may be possible to express the learning rate percentage ‘p’ as the product of a series of contributing factors:

$$p = p^{\alpha+\beta+\gamma+\delta+\cdots+\zeta}$$

$$= p^{\alpha} p^{\beta} p^{\gamma} p^{\delta} \cdots p^{\zeta}$$

where α, β, γ, δ . . . ζ are the indices of contribution with values between zero and unity such that:

$$\alpha + \beta + \gamma + \delta + \cdots + \zeta = 1$$

Applying this model to the basic unit or cumulative average learning equation:

$$M_A = M_1 A^{\tau}$$

where $\tau = \dfrac{\log(\mathrm{p})}{\log(2)}$

Decoposing: $$\tau = \frac{\alpha \log(\mathrm{p}) + \beta \log(\mathrm{p}) + \cdots + \zeta\log(\mathrm{p})}{\log(2)}$$

$$= \alpha\tau + \beta\tau + \gamma\tau + \delta\tau + \cdots + \zeta\tau$$

therefore, $$M_A = M_I A^{\alpha\tau} A^{\beta\tau} A^{\gamma\tau} \cdots A^{\zeta\tau}$$

This model has the benefit of flexibility. It allows for different environmental factors to be considered in different companies, on different sites, and for different products or processes. The model allows also for either continued learning or a saturation level depending on the ongoing influence or cessation of the causative factors. In this manner, it is possible to relate the unit learning model to a nonlinear pattern of logarithmic data, providing some knowledge is available, or providing a reasonable assumption can be made regarding the causative factors. The model also allows the representation of levels of effort or investment, which are considered to be above or below the "norm" for the area or type of product/project under scrutiny.

Furthermore, as a mathematical product it is commutative in that the contribution factors do not exhibit any predefined sequence, and the absolute effect of one is dependent on the existence or otherwise of the others. Its key feature is its flexibility in modeling a variety of scenarios including saturation learning.

Using the Segmented Learning Model to Test the Hypothesis That the Rate of Learning Is Dependent on the Rate of Production

Rationale. There is documented evidence that would support this hypothesis. Harvey [8] observed that in a study of 10 individual, but related, assembly tasks,

- A learning rate of 76 percent could be achieved if operators always performed the same task
- This rate would be reduced to 84 percent if operators were inhibited in building up this individual experience

This would suggest that some 37 percent of the learning was attributable to operator experience, while the other 63 percent was attributable to other factors. In practice, away from a controlled study environment, there would be a mixture of operator experience through constant repetition, and disruption through labor absences, transfers, and rate buildup, suggesting perhaps that the 22 percent Northrop value cited by Jefferson [2] is not unreasonable. The implication, however, is that there may be an optimum rate of learning, and potentially that would be when each operator performs the same task on every unit.

Wild [1] observes also that the "longer the task, in general, the slower the learning." There is an intuitive logic that learning is facilitated by a shorter repetition cycle, and that the effect is then iterative, leading to a steeper rate of learning.

Again intuitively, the ideal conditions for optimum learning require that an operator performs the same task on every unit. This is supported by empirical evidence [8], in that a greater learning can be achieved if operators are not switched between different tasks. In contrast, however, this poses a problem to the "modern" organization. It creates a dichotomy in respect of operator continuity/repetition and the need to provide variety and flexibility [9] (i.e., the human dimension of job satisfaction). This can be demonstrated hypothetically also:

Suppose, N is the total number of operators employed on an assembly project
W is the average labor-hours per operator worked in a time period
M is the average unit cost in labor-hours for equivalent units built in the time period
R is the rate of output in the time period

Clearly the total labor-hours can be expressed as the product of the number of operators and the labor-hours they work, and also as the product of the average cost per unit and the rate of output, i.e.,

$$NW = MR$$

Taking the basic premise that for maximum learning each operator must perform a unique task or work package on a given product with a stable design and method configuration, the only variability in the left-hand product term is the number of hours worked. To all intents and purposes, this can be assumed to be fairly static in the long term, as there is an upper limit to the effective capacity of an individual manual worker. If learning exists, M is monotonic decreasing by definition, and the rate of output R must therefore increase in inverse proportion. In practice, the output rate will not increase beyond a fixed or maximum level as defined by the customer's delivery requirements.

Under these circumstances, for learning to continue, it is clear that the number of operators must be reduced, but this in turn violates the initial premise for optimum learning, and so at least one task must be relearned by other operators in addition to their existing tasks, thus retarding but not necessarily truncating the learning.

Empirical Data: Example Regression. We must now test this hypothesis: Does the rate of output significantly affect the rate of learning?

Figure 17.10.4 depicts the historical cumulative deliveries and nominal output rates by month for Product A's fuselage assembly and Product B's flying surface assembly, respectively.

The regression model tests the hypothesis that there is a breakpoint in the unit learning curve relationship when a nominal constant output rate is achieved. In order to employ a linear regression technique, a dummy variable is created and logarithmic values of labor-hours and build units are used in the analysis.

Model to be tested: $M_A = M_I A^{\tau}$ for A ≤ B

$M_A = M_I B^{\tau-\sigma} A^{\sigma}$ for A ≥ B

where M_A = Labor-hours at unit A
M_I = Labor-hours at first unit
B = Unit at which the breakpoint is assumed to occur
(i.e., the unit at which a nominal maximum rate begins)
τ = Learning exponent before the breakpoint
σ = Learning exponent after the breakpoint

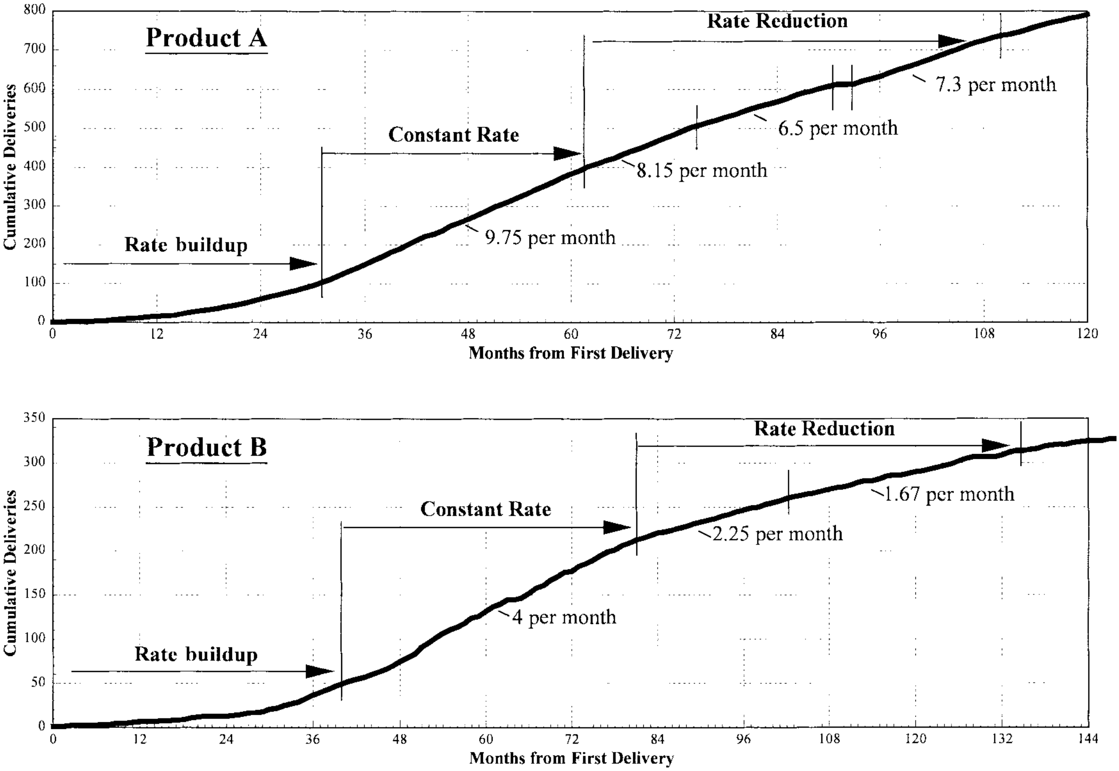

FIGURE 17.10.4 Cumulative product deliveries by month.

In order to use a simple linear regression technique, the previous model must first be adapted to read:

$$M_A = M_1 X^{\tau} Y^{\sigma}$$

such that

$$X = A \text{ for A} \le \text{B}$$

$$Y = 1 \text{ for A} \le \text{B}$$

$$X = B \text{ for A} \ge \text{B}$$

$$Y = \frac{A}{B} \text{ for A} \ge \text{B}$$

A linear transformation of this simplified model allows a multilinear regression to be performed:

$$\log(M_A) = \log(M_1) + \tau \log(X) + \sigma \log(Y)$$

For the model parameters to be significant at the 95 percent confidence level, the t-values need to satisfy the criterion $|t| > 1.96$ (two-sided students t-test). This tests the null hypothesis that the parameter value is equal to zero. The high values of $|t|$ recorded on both the tests in Table 17.10.1 suggest that some linear function of the independent variable contributes significantly to the dependent variable's behavior.

Note: Parameter values for $\log(M_1)$ were generated as a matter of course during the regression, and were significant at the 95 percent confidence level, but are largely immaterial for the purposes of testing this hypothesis.

In both cases the correlation coefficient R^2 is very high, being approximately 0.94 on Product A and 0.95 on Product B. This also supports the hypothesis that there is a linear relationship in the model tested. Table 17.10.1 summarizes also the net change in learning from the commencement of a "constant output" rate. Figures 17.10.5 and 17.10.6 illustrate the corresponding regression results.

With such a small sample it is impossible to say whether either of the two assemblies are typical or atypical of a generic relationship. Neither, from the simple model assumed, can it be deduced whether any other factors (such as ongoing engineering and tool improvements) could have caused or contributed to the effects observed. For instance, it is known that Product B had very little funding available for continuous engineering improvement, which could have contributed to the greater break effect at maximum rate. On the other hand, Product A was subject to a high customer-led modification program but had benefited from a higher level of preproduction investment, both of which could have contributed to the slower rate of learning before the breakpoint.

TABLE 17.10.1 Regression Results: Effects of Output Rate Constraint

Assembly type	Total records	Breakpoint position	Parameter estimate	Standard error of estimate	t-values	Equivalent learning rate	Proportion of learning affected
Product A (fuselage)	300	111.00	τ −0.4023	0.0085	−47.07	75.7%	100%
		9.75 per month	σ −0.3193	0.0175	−18.20	80.1%	79.4%
Product B (flying surface)	207	50.00	τ −0.4831	0.0107	−45.11	71.5%	100%
		4 per month	σ −0.2169	0.0125	−17.32	86%	44.9%

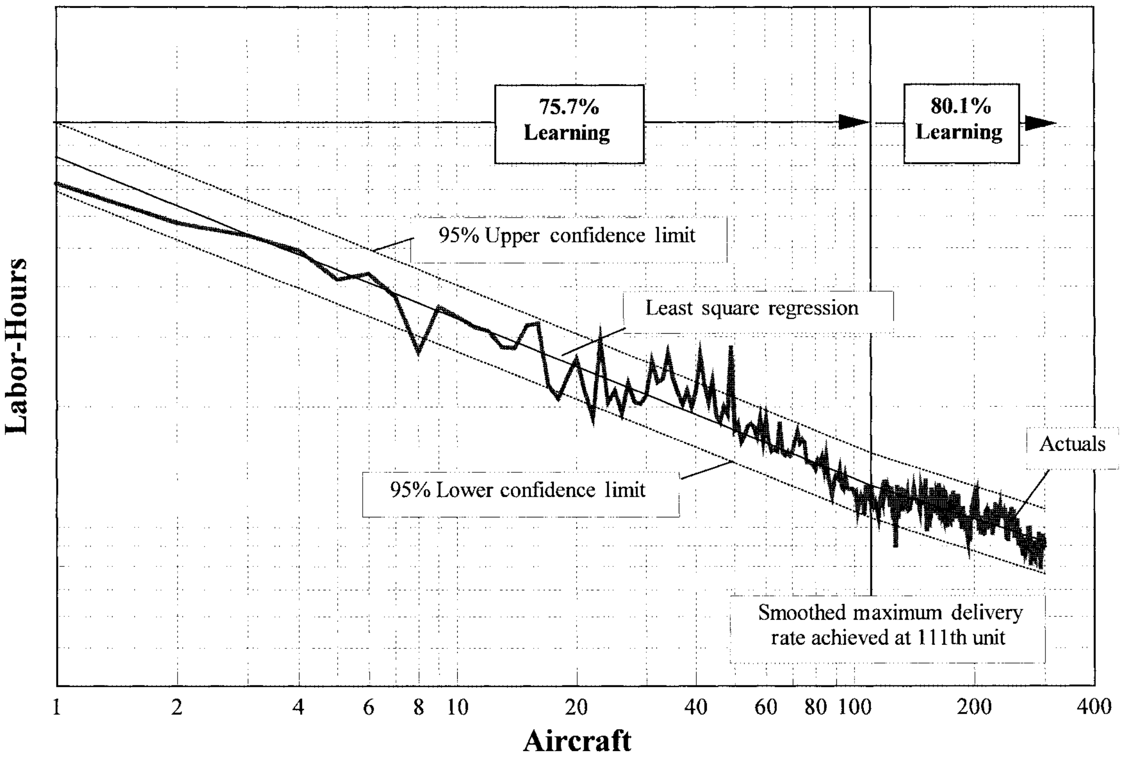

FIGURE 17.10.5 Assembly labor-hours—Product A.

Using Segmented Learning to Model Discontinuities in Production (Breaks and Transfers): The Concept of Relearning and Continued Learning

Rationale. The learning segmentation approach can be used to evaluate the effect of interfactory work transfers (second-source manufacture) and breaks in production, both of which have been observed by researchers, practitioners, and managers to be detrimental to learning.

- Conway and Schultz [4] observed the "disruptive effect" of work transfer, as did Smith [6].
- Harvey [8] observed at the operator experience level, that a 10-set break led to a 6 percent increase in labor-hours.
- Anderlohr [10] reported that 50 percent of learning was lost on a 3- to 6-month break, and up to 75 percent on 12+ month break.

Anderlohr proposed a methodology [10] for expressing the learning lost in the event of a break in production and this is discussed in Richard Engwall's article in Chap. 17.5.

In this case the learning relationship assumes the following form after the break:

$$M_A = M_1(\mathrm{A} - \mathrm{d})^{\tau}$$

where d is the equivalent number of units over which learning is deemed to have been lost (all other variables are as previously defined). Figure 17.10.7 illustrates this relationship.

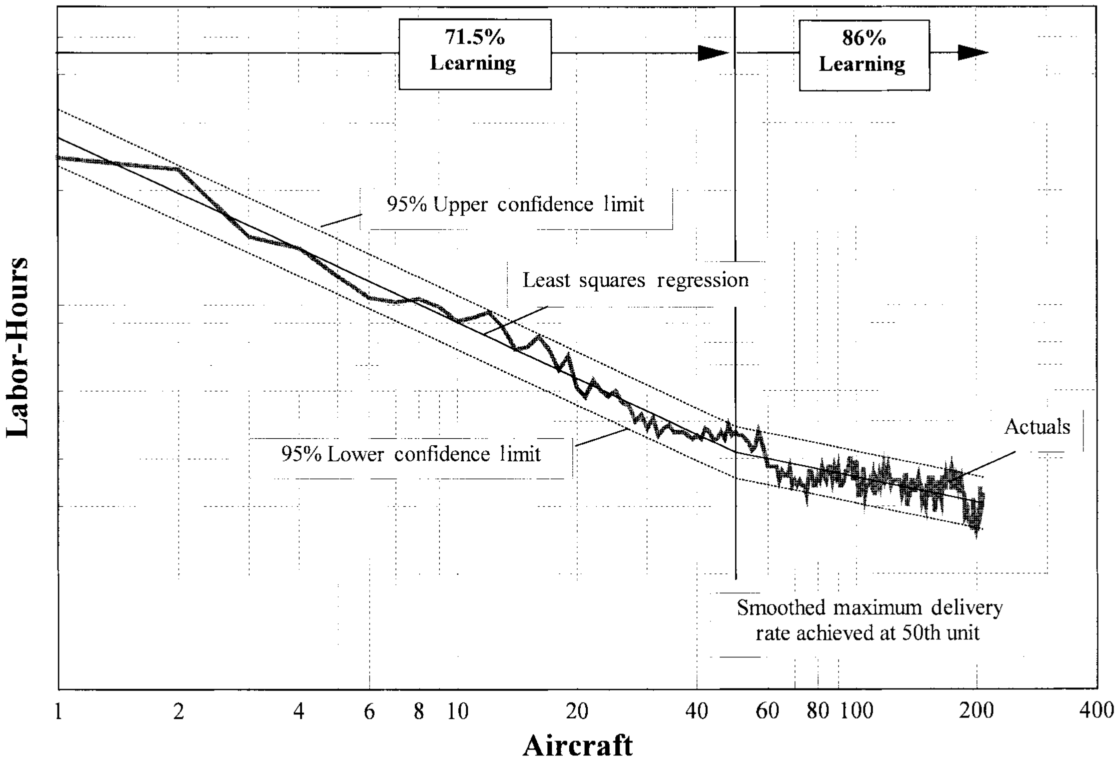

FIGURE 17.10.6 Assembly labor-hours—Product B.

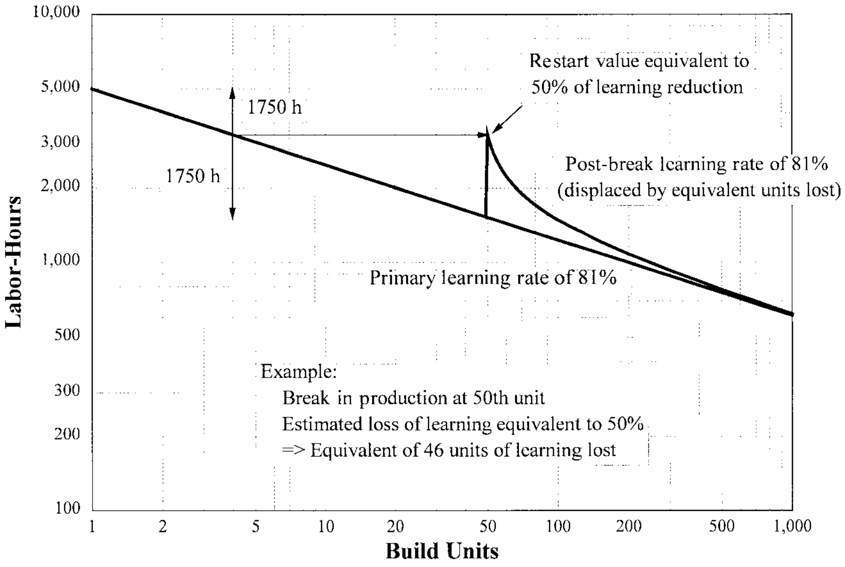

FIGURE 17.10.7 Assessing the effect of a break in production on learning—Anderlohr method.

An alternative method, similar in principle but different in the detail of how the "lost learning" is discounted, is to consider the concept of *segmented learning.* Here the discounted learning is applied to the rate of learning, not to the effective cumulative quantity manufactured. The residual learning is assumed to continue unaffected (see Fig. 17.10.8). The learning relationship after the break becomes:

$$M_A = M_1 A^{\delta\tau}(\mathrm{A} - \mathrm{B})^{(1-\delta)\tau}$$

where δ is the discount factor and B is the unit after which the break occurs.

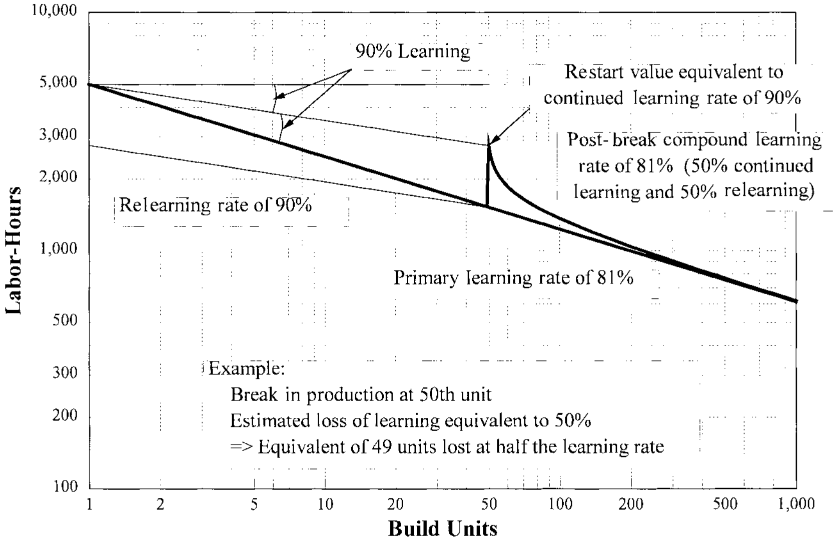

FIGURE 17.10.8 Assessing the effect of a break in production on learning—segmented learning method.

The advantage of the segmented learning model over that of the Anderlohr model is that regression analysis can be performed using a linear transformation and dummy variables. In Anderlohr's model, a nonlinear modeling technique must be used to calibrate the number of equivalent units of lost learning, unless a qualitative judgement is made beforehand to "fix" the parameter "*d.*" (Alternatively, the value "*d*" could be assessed by iteration by incrementing its value by 1, and looking for the best fit overall.)

This approach to "lost learning" can also be extended to other production discontinuities such as second-source manufacture (interfactory work transfer or relocation)—a feature of the aerospace industry that is not uncommon in the search for low-cost manufacture.

Empirical Data: Example Regression. Figure 17.10.9 depicts the historical deliveries by month for Product C's fuselage assembly, in which a three-year break in production was experienced.

The regression model tests the hypothesis that there is an element of continued learning after the break in production, and an element of relearning. The unit learning curve relationship is assumed. In order to employ a linear regression technique, a dummy variable is created and logarithmic values of labor-hours and build units are used in the analysis.

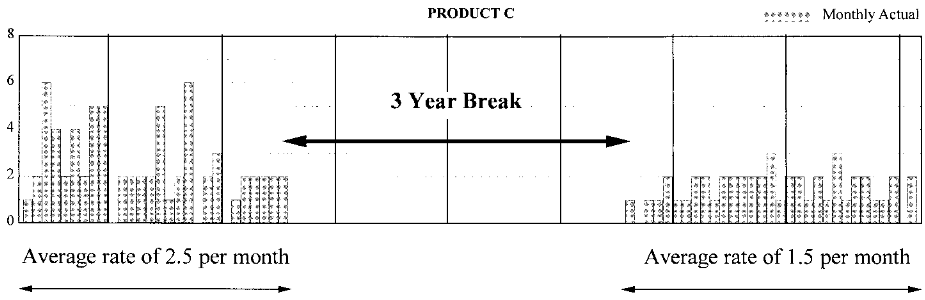

FIGURE 17.10.9 Break-in-production example.

Model to to be tested: $M_A = M_1 A^{\tau}$ for $A \leq B$

$$M_A = M_1 A^{\delta\tau} (A - B)^{(1-\delta)\tau} \quad \text{for } A > B$$

where M_A = Labor-hours at unit A
M_1 = Labor-hours at first unit
B = Unit after which the break in production occurred
τ = Learning exponent before the break
δ = The proportion of learning continued after the break

In order to use a simple linear regression technique, the above model must be first adapted to read:

$$M_A = M_1 X^{\varepsilon} Y^{\sigma}$$

such that
$X = A$
$Y = A$ for $A \leq B$
$Y = A - B$ for $A > B$
$\varepsilon = \delta\tau$
$\sigma = (1 - \delta)\tau$

A linear transformation of this simplified model allows a linear regression to be performed:

$$\log(M_A) = \log(M_1) + \varepsilon \log(X) + \sigma \log(Y)$$

For the model parameters to be significant at the 95 percent confidence level, the t-values need to satisfy the criterion $|t| > 1.96$ (two-sided students t-test). This tests the null hypothesis that the parameter value is equal to zero. The values of $|t|$ recorded on the test in Table 17.10.2 suggest that some linear function of the independent variable contributes to the dependent variable's behavior.

Note: Parameter values for $\log(M_1)$ were generated as a matter of course during the regression, and were significant at the 95 percent confidence level, but are largely immaterial for the purposes of testing this hypothesis.

Table 17.10.2 summarizes also the relative proportion of continued learning and relearning experienced following the three-year break in production. Figure 17.10.10 illustrates the regression results.

Based on a single example, it is impossible to say whether this is typical or atypical of a generic relationship. It must be recognized also that the learning rate before the break was already constrained by a limited output rate, and that this constraint became even more restrictive after the restart.

TABLE 17.10.2 Regression Results: Break in Production

Assembly type	Total records	Production break position	Parameter estimate	Standard error of estimate	t-values	Equivalent learning rate	Proportion of total learning
Product C	275	926	ε − 0.2274	0.0737	−3.087	85.4%	83.9%
			σ −0.0437	0.0048	−9.182	97.0%	16.1%
Ref only			τ −0.2711			82.8%	100%

Truncating Investment: "A Rule of Thumb"

Rationale. The learning segmentation approach also accommodates the effect of engineering improvements and other investments on learning. Unfortunately, although several authors have acknowledged this link, there appears to be little quantified evidence documented in the public domain. As engineering advancements continue to evolve, there is uncertainty over the benefits that will accrue. The effect of preproduction engineering and improved logistics control in the future are expected to be realized through shallower learning rates and reduced startup values.

Jefferson [2] observes that historically in the United States more is spent on investment throughout the life cycle than in the UK, and that consequently American learning rates continue over larger quantities. He also postulates on the effect of capital investment and government investment in research programs. His views led him to support the concept of discrete learning curve cost drivers.

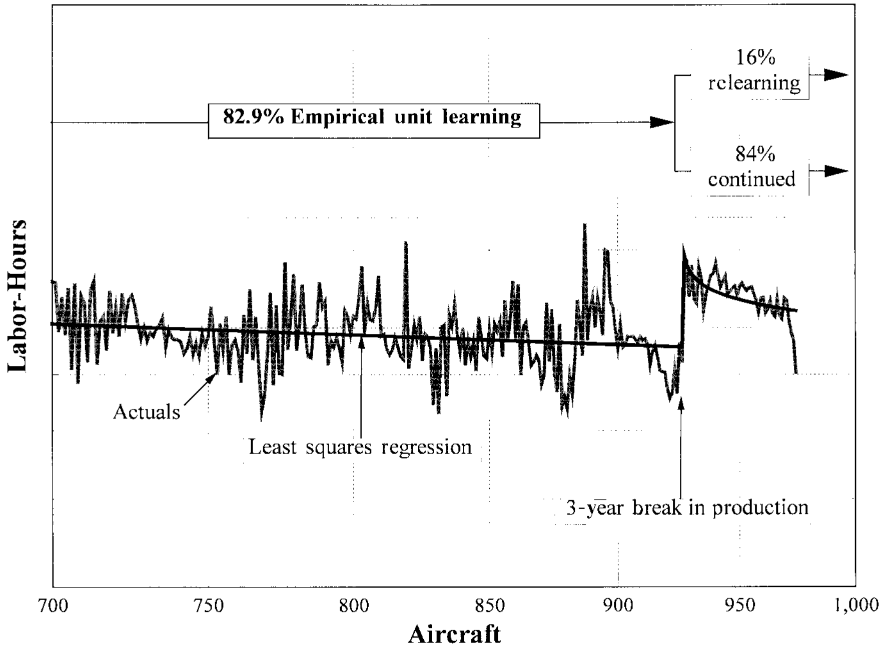

FIGURE 17.10.10 The effect of a break in production on learning.

Further study is obviously needed in this subject as the pace of technology development continues. It cannot simply be a case, for example, of looking for a correlation between engineering investment effort and the rate of learning, as ingenuity may reap greater rewards than sheer volume of effort or cost invested. However, in principle the concept of learning segmentation fits quite well with the contribution opportunity offered by various investments (i.e., the benefits are realized only if the investments are made).

Qualitative Argument: An Alternative to Empirical Evidence. There are circumstances where it may not be necessary or even possible to justify a hypothesis by statistical analysis. Qualitative argument may be an acceptable alternative in some cases.

Clearly, the potential cumulative savings on a learning curve attributable to any investment activity decreases as the build quantity remaining reduces. Heuristically (Fig. 17.10.11), potential savings diminish rapidly beyond the three-quarter quantity point. It could be inferred from this diagram that beyond this point any learning requiring an investment is less likely to provide an acceptable return or payback. This argument is supported by the tendency for many unit learning curves to flatten out during the latter stages of a production run. However, it does not preclude future investment, nor does it deny the possibility of future inspiration, but the argument does reflect the pragmatism of real life.

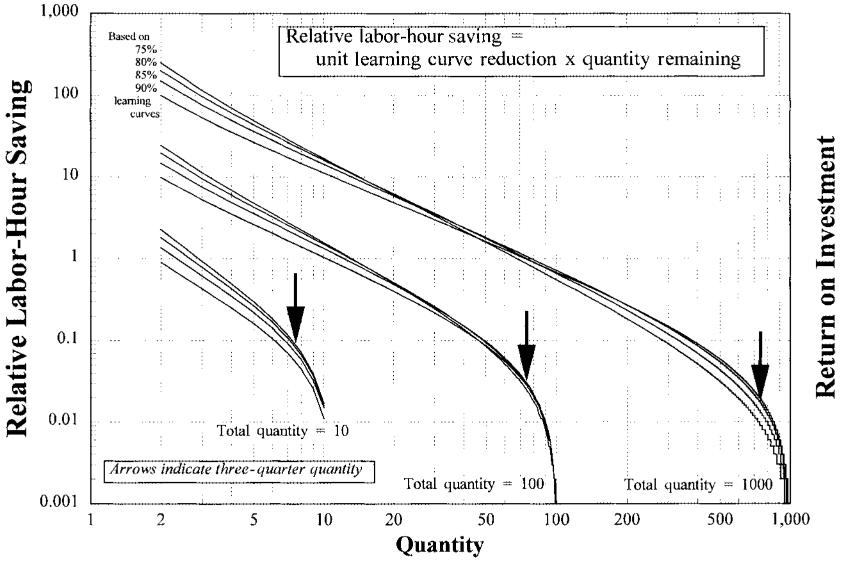

FIGURE 17.10.11 Potential cumulative learning curve savings.

IMPLEMENTATION OF CHANGES AND IMPROVEMENTS

The most difficult aspect of such a wide-ranging project is the limited access to relevant data. It is not the access to labor-hour data that is the problem; this is recorded and maintained to a very low level in accordance with U.K. MoD and U.S. DoD regulations. It is the access to data on the potential drivers that is problematic. Knowing if the data exists, and where to find it, is a major reason for involving a wider range of people in the process.

There were several potential drivers that could not be quantified readily because the historical data to support the analysis was not available. Critical component shortages or shortage levels is an example in question. It could be argued that there is little point in modeling data that cannot be forecast. (If you can forecast the shortage, why not prevent it!) However, if the analysis can be used to quantify a level of cost avoidance in support of a business case for an improved MRP system, for instance, then the analysis would be worthwhile. The level of design queries is another such example. The organization needs to address such issues and resolve the level at which it needs to maintain such data, and to what purpose.

RESULTS AND FUTURE ACTIONS

Segmented Learning Model

The evidence provided here is not conclusive, but it is encouraging, and more analysis is required. There is a need to model the effects and interactions of multiple drivers under different business conditions and scenarios in order to calibrate the model.

However, pragmatically, it would be difficult to calibrate a model, which captures the effects of all the potential causative factors at once. The engineer is urged to look for simplicity in the analysis stage, looking wherever possible for linear models, unless there is access to some robust nonlinear modeling package. It is advised that model development should be taken in stages, adding complexity only when there is a reasonable understanding of the constituent elements. However, an element of subjective judgement is likely to remain always, but it must be the aim to base this subjectivity on sound principles and logic.

Continuity of Learning

The current author is of the view that learning will continue for as long as there are enablers in place to allow it to continue; once these are removed, or exhausted, learning will truncate. The problem of predicting its eventuality remains.

The flexibility of the segmented model allows for either condition.

Footnote: Working with Cumulative Values

For all practical purposes, learning rates can be expected to be shallower than 50 percent. Within this range the unit learning curve is a diverging series (i.e., its summation diverges to infinity). The true cumulative total of a range of unit values from such a series, as might be required in estimating the value of a lot quantity, must be found by summation; there is no precise formula for the cumulative value. An estimate implies the acceptance of some error, and there are occasions in estimating when it is useful and quite acceptable to work with an approximation to the cumulative value. The asymptotic relationship of the unit curve to the cumulative average version does suggest that an acceptable approximation might be found. Conway and Schultz [4] offer the following relationship:

$$\text{Cumulative value, } C_A \simeq \frac{\mathrm{M}_1}{(\tau+1)}\left[(\mathrm{A}+0.5)^{\tau+1}-0.5^{\tau+1}\right]$$

The present author offers an alternative approximation formula:

$$\text{Cumulative value, } C_A \simeq \frac{\mathrm{M}_1}{(\tau+1)}\left(A^{\tau+1}-1\right)+\frac{\mathrm{M}_1}{2}\left(\mathrm{A}^{\tau}+1\right)$$

Neither relationship is valid for values of $\tau = -1$ (i.e., a learning rate equal to 50 percent). The principal difference between the two lies in the error term. The former always returns a positive error; the latter returns a negative error (Fig. 17.10.12). This property has some practical applications:

- Cost modeling across lot quantities is simplified.
- Learning curve trends can still be established even where batch-booking is a common practice, or the integrity of time bookings against individual units is called into question. Furthermore, it allows learning to be assessed where individual planeset bookings are not recorded, or the integrity of batch bookings only can be assured with any confidence.
- Incomplete units can be included on the basis of an equivalent aircraft completion.

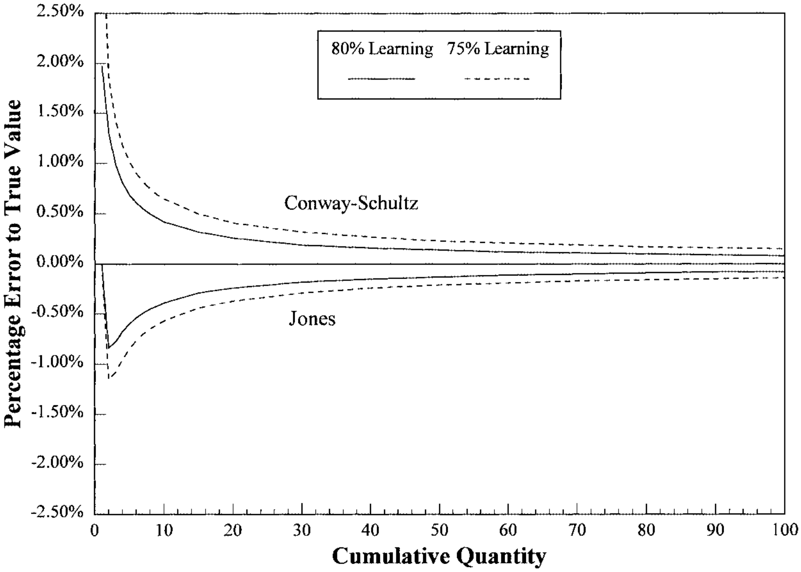

FIGURE 17.10.12 Cumulative value approximation errors.

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BIOGRAPHY

Alan Jones has a mathematics degree from the University of London, and a masters in business administration from Henley Management College in the U.K. He has worked with learning curves for over 20 years at BAE SYSTEMS (formerly British Aerospace) in a variety of roles including project engineer, industrial engineer, production estimator, and in business process development. During the 1980s he developed the concept of segmenting the learning curve as described in the case study and continues to use this approach.

CHAPTER 17.10

CASE STUDY: APPLYING LEARNING CURVES IN AIRCRAFT PRODUCTION—PROCEDURES AND EXPERIENCES

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Learning curves are used in aircraft production to estimate, budget, and control levels of resource and to assess contract performance. Learning is an empirical relationship, and as such the engineer or analyst must learn to recognize and deal with the practical problems of data analysis and modeling, including the exploitation of basic learning curve properties. This chapter will discuss the use of alternative forms of the learning relationship, principally the unit and cumulative average learning curves, and illustrate how these can be used to good effect within a manufacturing company. This chapter also demonstrates how it is possible to segment learning curves into discrete elements to model the effects of variations in specific cost drivers. Examples and techniques are discussed.

BACKGROUND AND SITUATION ANALYSIS

Introduction

The precise nature and cause of the learning phenomenon is not fully understood. As a consequence there are differences of opinion and interpretation across the industries that experience it. This case study illustrates an approach adopted by BAE SYSTEMS, and offers a route by which to quantify the issues propounded by Richard Engwall in Chap. 17.5. There are other approaches that are equally valid.

Definition of Learning

Learning can be defined [1] as "*the process by which an individual acquires skill and proficiency at a task, which in turn has the effect of permitting increased productivity in his or her performance of that task.*"

The cumulative effect within an organization of several individuals' learning could be considered to be that organization's learning. Northrop's definition of organizational learning [2] from the early 1960s states: "*A learning curve is the rate at which management identifies and solves problems in relation to design, methods, shortage of parts, inspection, and shop education.*"

Neither definition excludes the other; indeed one is an enabler or driver to the other. It is around a combination of these definitions that this case study is based.

In some ways it is fitting that some 32 years after the Wright brothers' pioneering first flight that another Wright [3] should pioneer the use of the learning phenomenon in forecasting the cost of aircraft manufacturing. Wright observed that the cumulative average labor hours followed a learning relationship, but many other authors have also mooted and applied learning to the unit labor-hour costs. Whichever model is used, it must be remembered that learning is an empirical relationship (i.e., based on observations, not mere theory).

Unit or Cumulative Average Learning: The Choice

While the cumulative average learning relationship has the benefit of its smoothing property [4] over the unit version, this same property does have the drawback of amortizing the cost of common and peculiar elements of work over the production run, as illustrated in Fig. 17.10.1. Consequently, where there is a high degree of peculiar work content, the cumulative average version has the tendency to disguise and amortize the true learning effects.

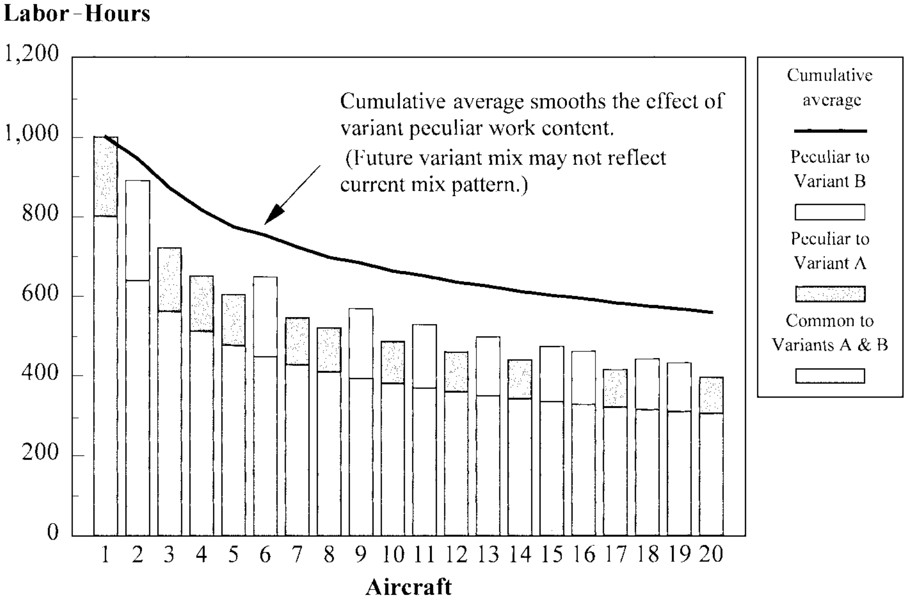

FIGURE 17.10.1 Disadvantage of cumulative average smoothing.

For the analysis of similar units (low peculiar work content), the two relationships are effectively interchangeable. In some respects, data might be more easily fitted by considering the cumulative average version of this curve, as only batch or lot totals are required, not individual cumulative average values. Whichever model is chosen, it must reflect the circumstances (in the widest sense) in which it is going to be applied. Learning is not a tool for the industrial historian, but rather for the engineer who wants to use it to imply knowledge or expectation about some future event, hopefully with the intention of influencing it.

Drivers of Learning Within Aerospace

In order to influence learning, an organization needs to have some understanding of what enables or inhibits learning in either a generic sense, or in the context of its own operating practices. This is not as easy as it sounds; learning is described as a complex subject influenced by a number of factors [1]. Numerous writers have observed and substantiated that learning is not solely the result of operator experience and/or motivation, but is dependent also on the engineering investment and operational conditions and constraints [4].

Jefferson [2] expresses the view that learning is the net effect of several factors, and cites the experience of Northrop in quantifying the principal enablers of learning (Fig. 17.10.2). Unfortunately, the supporting evidence is not provided, so the reader is left to speculate on its value and its interpretation in a wider or alternative environment.

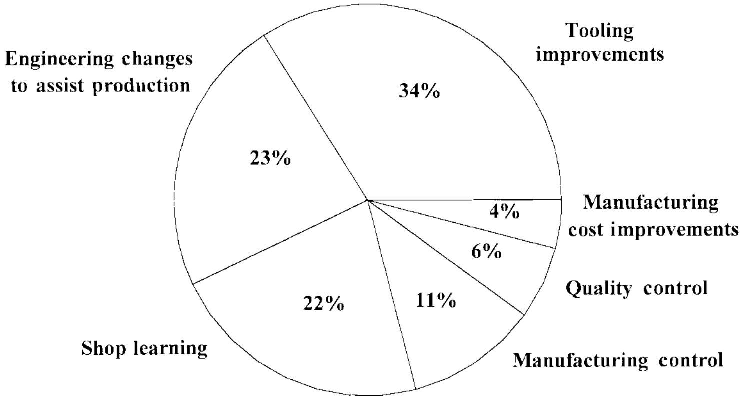

FIGURE 17.10.2 The constituent elements of production learning. (*Source: P Jefferson, "Productivity Comparisons with the USA—where do we differ?,"* Aeronautical Journal, *Vol. 85 No. 844, May 1981, p. 179.*)

However, as no two organizations are alike, there are probably no universal values; Jacobs [5] postulates that "*cost is the final measure of everyone's inefficiencies.*" Smith [6] observes that different learning rates exist between similar products at different locations, and accepts that this is the influence of causal factors.

If learning is so difficult to predict accurately, or understand, does it really matter? It is a question of degree. It is not necessary—and probably not possible—to understand every nuance of the learning curve. Learning is an empirical relationship, not a mathematical axiom; it can provide an estimate, not a precise measurement. However, it is necessary that an organization understands the major causes and drivers of learning that it experiences. Failure to do so may result in reduced profits or lost business. An error of 1 percent in the rate of learning assumed aggregates to a cumulative error of 6 percent over 100 units and 10 percent over 1000.

Learning: Where Does It End?

Does learning continue indefinitely, or does it have a finite limit? If it does, where or when does this occur? These are issues which have been much debated across negotiating tables and in the pages of respected journals for many years—and probably will continue to be for many more.

To allow for concerns about the perpetuity of learning, a variation of the unit learning curve is that of a finite learning model, which assumes that learning will reach a saturation point. There is documented support [7] for the finite learning model, in which it is assumed that there is an incompressible lower limit to the learning phenomenon.

Although intuitively this has some appeal, its major drawback in practice is that it requires either a nonlinear technique to calibrate the model from actual data, or a supposition about the saturation level. (Even a standard time value is not necessarily a practical assumption, as the engineering definition and solution are likely to be modified in order to achieve productivity improvement targets inherent in the learning function.)

Harvey [8] reflects also on the tendency for learning to flatten after about 100 units within the U.K. aircraft industry, but does recognize also that this is not necessarily acceptable, affirming the need for continuous learning in response to market drivers. He considers also the argument of continuous and saturated learning as being somewhat academic [9], as wartime experience in the United States showed continuity of learning into tens of thousands of units. It could be countered, somewhat cynically perhaps, that this is just a measure of how inefficient it can be at the onset of a crisis situation such as war, and that the continuing need drove the improvement!

Protagonists of the finite learning argument observe that learning often flattens off before the end of a production run. This is not merely a linear perspective of an exponential function, but one that can be illustrated by a log-log plot also. The real question is not does it occur, but why and when?

OBJECTIVES AND SCOPE

The primary objective of this case study was to identify a framework in which to assess the impact on learning of a variety of business scenarios in recurring production aircraft activities. The framework was required to be both practical and flexible, and capable of being used for both data analysis and forecasting at a high level. It was not the intention to provide a tool for detailed cause-and-effect analysis at the operational level, as the reaction time over an aircraft build stage was considered to be too slow to be of benefit at that level. It is far better to prevent a problem than to have to cure one.

The scope of the study was to be limited initially to assembly data, as this represented the area in which traditionally more marked learning rates are observed. However, consideration of learning in other areas was not to be excluded specifically.

The suitability of the proposed framework was to be demonstrated by addressing three specific issues:

- Does the rate of production have a significant impact on the rate of learning?
- How can the disruptive effects of work transfers and breaks in production be quantified in advance, or even be controlled?
- Why is learning often observed to truncate significantly before the end of production? Does learning have a saturation level?

ORGANIZATION OF THE PROJECT

The project called for the following four distinct phases or activities to be performed.

Literature Search

It is always good practice to review the work of others. No one person or organization has a monopoly of good ideas, knowledge, or experience. Lessons learned or observed by others can help to direct another's thinking or to avert nugatory work. The major benefit is that it highlights the areas of common knowledge and substantiation to date, and underlines the areas of ignorance or supposition. The difficulty is finding the existing research that is relevant to the case study.

Choice of Model

A number of mathematical models on learning have been developed, as the literature search highlights. The one chosen had to satisfy two basic criteria:

- It had to be flexible enough to be used to model the resource requirements implicit in alternative business scenarios.
- It had to be simple enough to be in a format that could be used with any standard data analysis package available to engineers in an office environment.

It was in this phase where the various hypotheses would be developed and a generic model compiled.

Data Sampling and Regression Analysis

This phase required the use of standard data analysis techniques such as linear regression and correlation. Actual data was to be gathered relating to the observed labor hours and the hypothesis or event to be tested. In some respects, this phase would prove to be the most challenging; labor-hour data was readily available, because of the requirements placed on defense contractors to maintain records, but historical records of other types are not always available. This would either limit the range of scenarios that could be tested, or require the use of estimated data. In terms of the results documented in this case study, the former applies.

Involvement

Unless an organization is quite small, it is unlikely that any one person will be able to postulate and understand all the drivers of learning for that organization. It is important that others be involved during the process:

- Those who are involved in the product delivery to identify the obstacles and constraints to efficiency
- Those who can stand back and take a wider perspective and draw links to wider business issues

Discussions with such subject matter experts are essential before and after the data analysis stage in order to test the sensibility of the analysis, and to gain acceptance of the results.

PROCEDURE AND APPLICATION OF TOOLS

Choice of Model: Alternative Forms of the Learning Curve and Their Applications

In selecting the appropriate learning model it was recognized that there were alternatives and variations to the cumulative average and unit learning versions that needed to be considered.

Finite Learning Model (Saturated Learning). In its simplest form, this can be expressed as a variation on the unit learning curve:

$$M_A = M_S + M_V A^{\tau}$$

where M_A = labor-hour value at Unit A
M_V = variable labor-hour value of the first unit
M_S = labor-hour learning saturation level
τ = the learning exponent, defined by the relationship
$\tau = \log(p)/\log(2)$

with p being the learning percentage expressed as a decimal (e.g., 80% = > 0.8).

$$M_1 = M_S + M_V = \text{total labor-hour value of the first unit}$$

As an alternative to the finite learning model, it is common practice to utilize breakpoints (Fig. 17.10.3) to represent a change in the rate of learning.

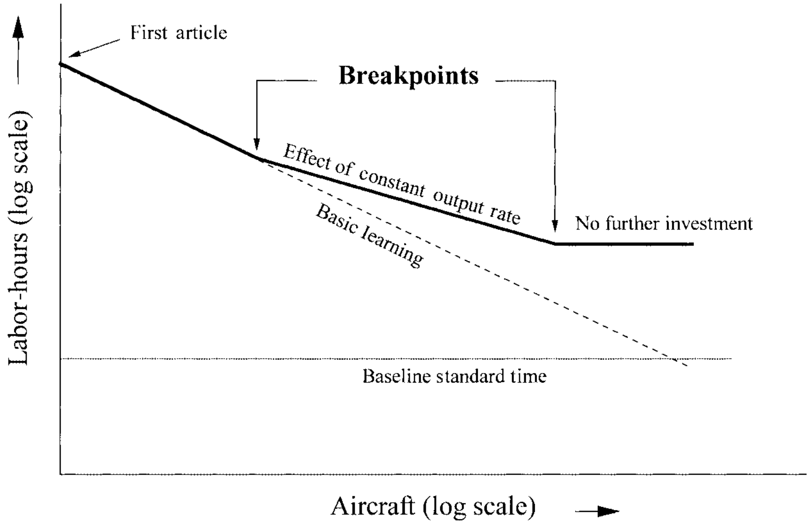

FIGURE 17.10.3 Example of learning curve breakpoints.

Modeling Discontinuities in Learning. Observation of numerous tasks which exhibit learning characteristics reveal that the phenomenon of breakpoints does appear to occur. The impact of a breakpoint can be reflected mathematically:

$$M_A = M_1 A^{\tau} \qquad \text{for } A \le B$$

$$M_A = M_1 B^{\tau - \sigma} A^{\sigma} \qquad \text{for } A \ge B$$

where M_A = Labor-hours at unit A
M_1 = Labor-hours at first unit
B = Point at which the breakpoint is assumed to occur
τ = Learning exponent before the breakpoint
σ = Learning exponent after the breakpoint

The main benefit of this model over the finite learning model is that it can reflect the saturation condition, while still being in a form that can be transformed into a linear model for analysis:

$$M_A = M_1 X^{\tau} Y^{\sigma}$$

such that

$$X = A \text{ for } A \leq B$$

$$Y = 1 \text{ for } A \leq B$$

$$X = B \text{ for A} \geq B$$

$$Y = \frac{A}{B} \text{ for } A \geq B$$

A linear transformation of this simplified model allows a multilinear regression to be performed:

$$\log(M_A) = \log(M_1) + \tau \log(\mathrm{X}) + \sigma \log(\mathrm{Y})$$

Segmenting the Learning Curve—The Concept of Cost Drivers

However, accepting the observation of multiple drivers as being valid in principle, if it were possible to express the cumulative effect of each driver in relation to the cumulative quantity produced, it suggests that it may be possible to express the learning rate percentage ‘p’ as the product of a series of contributing factors:

$$\begin{aligned} p &= p^{\alpha+\beta+\gamma+\delta+\cdots+\zeta} \\ &= p^{\alpha} p^{\beta} p^{\gamma} p^{\delta} \cdots p^{\zeta} \end{aligned}$$

where $\alpha, \beta, \gamma, \delta \ldots \zeta$ are the indices of contribution with values between zero and unity such that:

$$\alpha + \beta + \gamma + \delta + \cdots + \zeta = 1$$

Applying this model to the basic unit or cumulative average learning equation:

$$M_A = M_1 A^{\tau}$$

where $\tau = \dfrac{\log(\mathrm{p})}{\log(2)}$

Decoposing: $$\tau = \frac{\alpha \log(\mathrm{p}) + \beta \log(\mathrm{p}) + \cdots + \zeta \log(\mathrm{p})}{\log(2)}$$

$$= \alpha\tau + \beta\tau + \gamma\tau + \delta\tau + \cdots + \zeta\tau$$

therefore, $$M_A = M_I A^{\alpha\tau} A^{\beta\tau} A^{\gamma\tau} \cdots A^{\zeta\tau}$$

This model has the benefit of flexibility. It allows for different environmental factors to be considered in different companies, on different sites, and for different products or processes. The model allows also for either continued learning or a saturation level depending on the ongoing influence or cessation of the causative factors. In this manner, it is possible to relate the unit learning model to a nonlinear pattern of logarithmic data, providing some knowledge is available, or providing a reasonable assumption can be made regarding the causative factors. The model also allows the representation of levels of effort or investment, which are considered to be above or below the "norm" for the area or type of product/project under scrutiny.

Furthermore, as a mathematical product it is commutative in that the contribution factors do not exhibit any predefined sequence, and the absolute effect of one is dependent on the existence or otherwise of the others. Its key feature is its flexibility in modeling a variety of scenarios including saturation learning.

Using the Segmented Learning Model to Test the Hypothesis That the Rate of Learning Is Dependent on the Rate of Production

Rationale. There is documented evidence that would support this hypothesis. Harvey [8] observed that in a study of 10 individual, but related, assembly tasks,

- A learning rate of 76 percent could be achieved if operators always performed the same task
- This rate would be reduced to 84 percent if operators were inhibited in building up this individual experience

This would suggest that some 37 percent of the learning was attributable to operator experience, while the other 63 percent was attributable to other factors. In practice, away from a controlled study environment, there would be a mixture of operator experience through constant repetition, and disruption through labor absences, transfers, and rate buildup, suggesting perhaps that the 22 percent Northrop value cited by Jefferson [2] is not unreasonable. The implication, however, is that there may be an optimum rate of learning, and potentially that would be when each operator performs the same task on every unit.

Wild [1] observes also that the "longer the task, in general, the slower the learning." There is an intuitive logic that learning is facilitated by a shorter repetition cycle, and that the effect is then iterative, leading to a steeper rate of learning.

Again intuitively, the ideal conditions for optimum learning require that an operator performs the same task on every unit. This is supported by empirical evidence [8], in that a greater learning can be achieved if operators are not switched between different tasks. In contrast, however, this poses a problem to the "modern" organization. It creates a dichotomy in respect of operator continuity/repetition and the need to provide variety and flexibility [9] (i.e., the human dimension of job satisfaction). This can be demonstrated hypothetically also:

Suppose, N is the total number of operators employed on an assembly project
W is the average labor-hours per operator worked in a time period
M is the average unit cost in labor-hours for equivalent units built in the time period
R is the rate of output in the time period

Clearly the total labor-hours can be expressed as the product of the number of operators and the labor-hours they work, and also as the product of the average cost per unit and the rate of output, i.e.,

$$NW = MR$$

Taking the basic premise that for maximum learning each operator must perform a unique task or work package on a given product with a stable design and method configuration, the only variability in the left-hand product term is the number of hours worked. To all intents and purposes, this can be assumed to be fairly static in the long term, as there is an upper limit to the effective capacity of an individual manual worker. If learning exists, M is monotonic decreasing by definition, and the rate of output R must therefore increase in inverse proportion. In practice, the output rate will not increase beyond a fixed or maximum level as defined by the customer's delivery requirements.

Under these circumstances, for learning to continue, it is clear that the number of operators must be reduced, but this in turn violates the initial premise for optimum learning, and so at least one task must be relearned by other operators in addition to their existing tasks, thus retarding but not necessarily truncating the learning.

Empirical Data: Example Regression. We must now test this hypothesis: Does the rate of output significantly affect the rate of learning?

Figure 17.10.4 depicts the historical cumulative deliveries and nominal output rates by month for Product A's fuselage assembly and Product B's flying surface assembly, respectively.

The regression model tests the hypothesis that there is a breakpoint in the unit learning curve relationship when a nominal constant output rate is achieved. In order to employ a linear regression technique, a dummy variable is created and logarithmic values of labor-hours and build units are used in the analysis.

Model to be tested: $M_A = M_1 A^{\tau}$ for $A \le B$

$M_A = M_1 B^{\tau - \sigma} A^{\sigma}$ for $A \ge B$

where M_A = Labor-hours at unit A
M_1 = Labor-hours at first unit
B = Unit at which the breakpoint is assumed to occur
(i.e., the unit at which a nominal maximum rate begins)
τ = Learning exponent before the breakpoint
σ = Learning exponent after the breakpoint

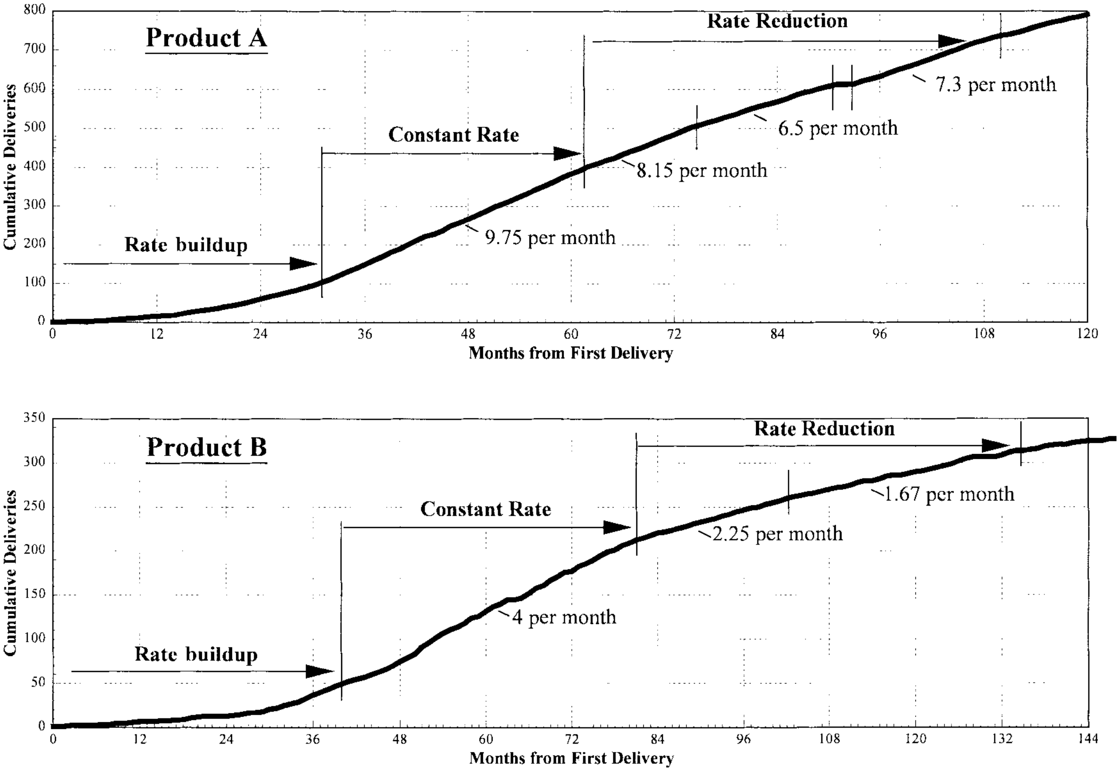

FIGURE 17.10.4 Cumulative product deliveries by month.

In order to use a simple linear regression technique, the previous model must first be adapted to read:

$$M_A = M_1 X^{\tau} Y^{\sigma}$$

such that

$$X = A \text{ for A} \le \text{B}$$

$$Y = 1 \text{ for A} \le \text{B}$$

$$X = B \text{ for A} \ge \text{B}$$

$$Y = \frac{A}{B} \text{ for A} \ge \text{B}$$

A linear transformation of this simplified model allows a multilinear regression to be performed:

$$\log(M_A) = \log(M_1) + \tau \log(X) + \sigma \log(Y)$$

For the model parameters to be significant at the 95 percent confidence level, the t-values need to satisfy the criterion $|t| > 1.96$ (two-sided students t-test). This tests the null hypothesis that the parameter value is equal to zero. The high values of $|t|$ recorded on both the tests in Table 17.10.1 suggest that some linear function of the independent variable contributes significantly to the dependent variable's behavior.

Note: Parameter values for $\log(M_1)$ were generated as a matter of course during the regression, and were significant at the 95 percent confidence level, but are largely immaterial for the purposes of testing this hypothesis.

In both cases the correlation coefficient R^2 is very high, being approximately 0.94 on Product A and 0.95 on Product B. This also supports the hypothesis that there is a linear relationship in the model tested. Table 17.10.1 summarizes also the net change in learning from the commencement of a "constant output" rate. Figures 17.10.5 and 17.10.6 illustrate the corresponding regression results.

With such a small sample it is impossible to say whether either of the two assemblies are typical or atypical of a generic relationship. Neither, from the simple model assumed, can it be deduced whether any other factors (such as ongoing engineering and tool improvements) could have caused or contributed to the effects observed. For instance, it is known that Product B had very little funding available for continuous engineering improvement, which could have contributed to the greater break effect at maximum rate. On the other hand, Product A was subject to a high customer-led modification program but had benefited from a higher level of preproduction investment, both of which could have contributed to the slower rate of learning before the breakpoint.

TABLE 17.10.1 Regression Results: Effects of Output Rate Constraint

Assembly type	Total records	Breakpoint position	Parameter estimate	Standard error of estimate	t-values	Equivalent learning rate	Proportion of learning affected
Product A (fuselage)	300	111.00	τ −0.4023	0.0085	−47.07	75.7%	100%
		9.75 per month	σ −0.3193	0.0175	−18.20	80.1%	79.4%
Product B (flying surface)	207	50.00	τ −0.4831	0.0107	−45.11	71.5%	100%
		4 per month	σ −0.2169	0.0125	−17.32	86%	44.9%

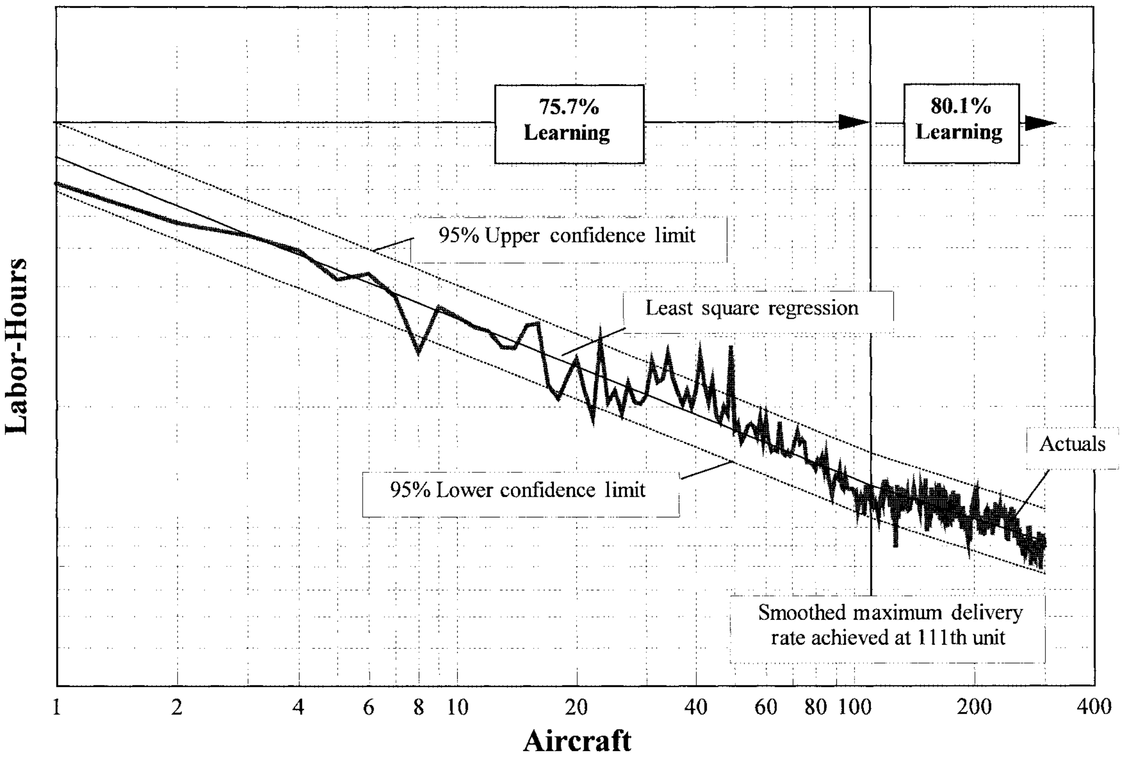

FIGURE 17.10.5 Assembly labor-hours—Product A.

Using Segmented Learning to Model Discontinuities in Production (Breaks and Transfers): The Concept of Relearning and Continued Learning

Rationale. The learning segmentation approach can be used to evaluate the effect of interfactory work transfers (second-source manufacture) and breaks in production, both of which have been observed by researchers, practitioners, and managers to be detrimental to learning.

- Conway and Schultz [4] observed the "disruptive effect" of work transfer, as did Smith [6].
- Harvey [8] observed at the operator experience level, that a 10-set break led to a 6 percent increase in labor-hours.
- Anderlohr [10] reported that 50 percent of learning was lost on a 3- to 6-month break, and up to 75 percent on 12+ month break.

Anderlohr proposed a methodology [10] for expressing the learning lost in the event of a break in production and this is discussed in Richard Engwall's article in Chap. 17.5.

In this case the learning relationship assumes the following form after the break:

$$M_A = M_1(\mathrm{A} - \mathrm{d})^{\tau}$$

where d is the equivalent number of units over which learning is deemed to have been lost (all other variables are as previously defined). Figure 17.10.7 illustrates this relationship.

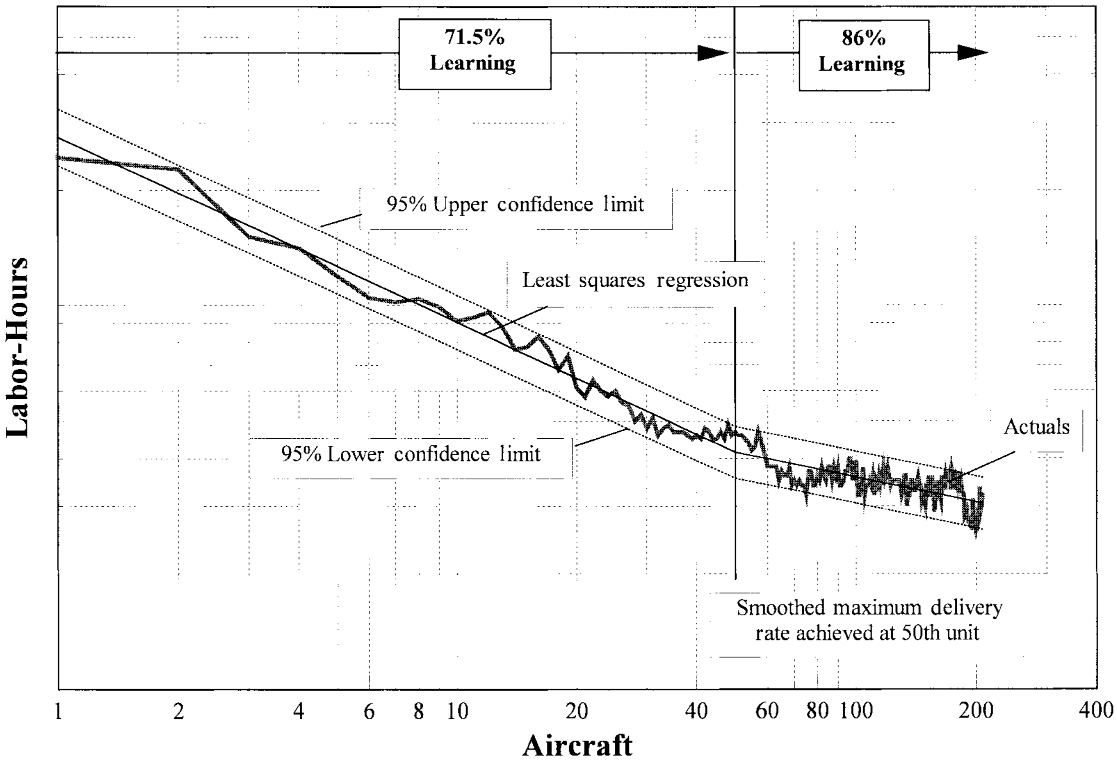

FIGURE 17.10.6 Assembly labor-hours—Product B.

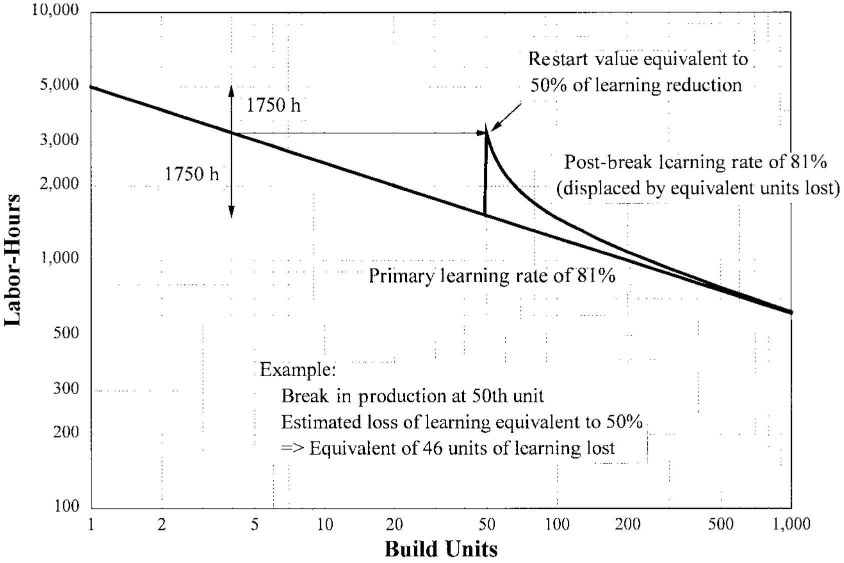

FIGURE 17.10.7 Assessing the effect of a break in production on learning—Anderlohr method.

An alternative method, similar in principle but different in the detail of how the "lost learning" is discounted, is to consider the concept of *segmented learning.* Here the discounted learning is applied to the rate of learning, not to the effective cumulative quantity manufactured. The residual learning is assumed to continue unaffected (see Fig. 17.10.8). The learning relationship after the break becomes:

$$M_A = M_1 A^{\delta\tau}(A - B)^{(1-\delta)\tau}$$

where δ is the discount factor and B is the unit after which the break occurs.

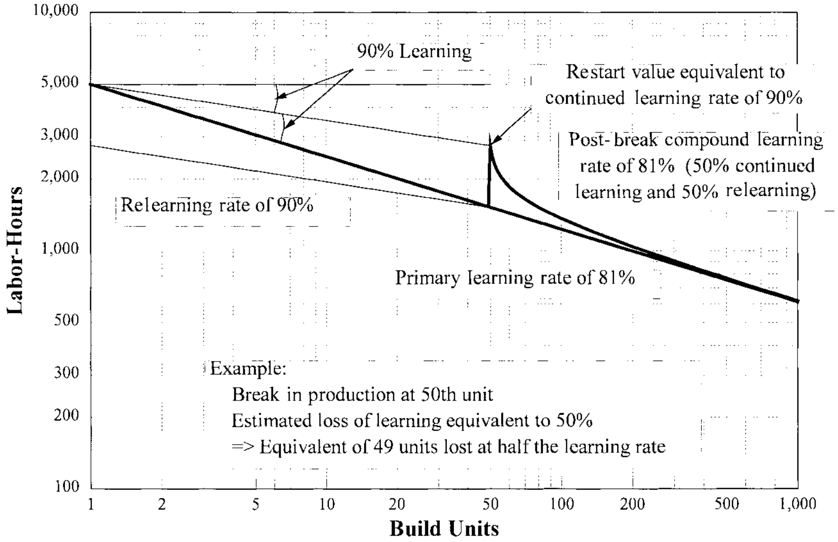

FIGURE 17.10.8 Assessing the effect of a break in production on learning—segmented learning method.

The advantage of the segmented learning model over that of the Anderlohr model is that regression analysis can be performed using a linear transformation and dummy variables. In Anderlohr's model, a nonlinear modeling technique must be used to calibrate the number of equivalent units of lost learning, unless a qualitative judgement is made beforehand to "fix" the parameter "*d.*" (Alternatively, the value "*d*" could be assessed by iteration by incrementing its value by 1, and looking for the best fit overall.)

This approach to "lost learning" can also be extended to other production discontinuities such as second-source manufacture (interfactory work transfer or relocation)—a feature of the aerospace industry that is not uncommon in the search for low-cost manufacture.

Empirical Data: Example Regression. Figure 17.10.9 depicts the historical deliveries by month for Product C's fuselage assembly, in which a three-year break in production was experienced.

The regression model tests the hypothesis that there is an element of continued learning after the break in production, and an element of relearning. The unit learning curve relationship is assumed. In order to employ a linear regression technique, a dummy variable is created and logarithmic values of labor-hours and build units are used in the analysis.

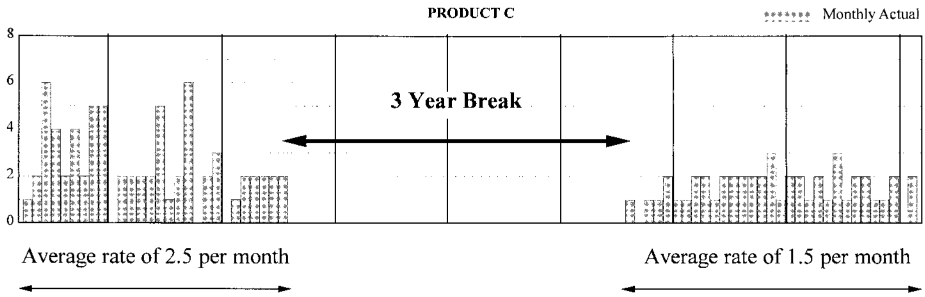

FIGURE 17.10.9 Break-in-production example.

Model to be tested: $M_A = M_1 A^{\tau}$ for $A \leq B$

$M_A = M_1 A^{\delta\tau} (A - B)^{(1-\delta)\tau}$ for $A > B$

where M_A = Labor-hours at unit A
M_1 = Labor-hours at first unit
B = Unit after which the break in production occurred
τ = Learning exponent before the break
δ = The proportion of learning continued after the break

In order to use a simple linear regression technique, the above model must be first adapted to read:

$$M_A = M_1 X^{\varepsilon} Y^{\sigma}$$

such that $X = A$
$Y = A$ for $A \leq B$
$Y = A - B$ for $A > B$
$\varepsilon = \delta\tau$
$\sigma = (1 - \delta)\tau$

A linear transformation of this simplified model allows a linear regression to be performed:

$$\log(M_A) = \log(M_1) + \varepsilon \log(X) + \sigma \log(Y)$$

For the model parameters to be significant at the 95 percent confidence level, the t-values need to satisfy the criterion $|t| > 1.96$ (two-sided students t-test). This tests the null hypothesis that the parameter value is equal to zero. The values of $|t|$ recorded on the test in Table 17.10.2 suggest that some linear function of the independent variable contributes to the dependent variable's behavior.

Note: Parameter values for $\log(M_1)$ were generated as a matter of course during the regression, and were significant at the 95 percent confidence level, but are largely immaterial for the purposes of testing this hypothesis.

Table 17.10.2 summarizes also the relative proportion of continued learning and relearning experienced following the three-year break in production. Figure 17.10.10 illustrates the regression results.

Based on a single example, it is impossible to say whether this is typical or atypical of a generic relationship. It must be recognized also that the learning rate before the break was already constrained by a limited output rate, and that this constraint became even more restrictive after the restart.

TABLE 17.10.2 Regression Results: Break in Production

Assembly type	Total records	Production break position	Parameter estimate	Standard error of estimate	t-values	Equivalent learning rate	Proportion of total learning
Product C	275	926	ε − 0.2274	0.0737	−3.087	85.4%	83.9%
			σ −0.0437	0.0048	−9.182	97.0%	16.1%
Ref only			τ −0.2711			82.8%	100%

Truncating Investment: "A Rule of Thumb"

Rationale. The learning segmentation approach also accommodates the effect of engineering improvements and other investments on learning. Unfortunately, although several authors have acknowledged this link, there appears to be little quantified evidence documented in the public domain. As engineering advancements continue to evolve, there is uncertainty over the benefits that will accrue. The effect of preproduction engineering and improved logistics control in the future are expected to be realized through shallower learning rates and reduced startup values.

Jefferson [2] observes that historically in the United States more is spent on investment throughout the life cycle than in the UK, and that consequently American learning rates continue over larger quantities. He also postulates on the effect of capital investment and government investment in research programs. His views led him to support the concept of discrete learning curve cost drivers.

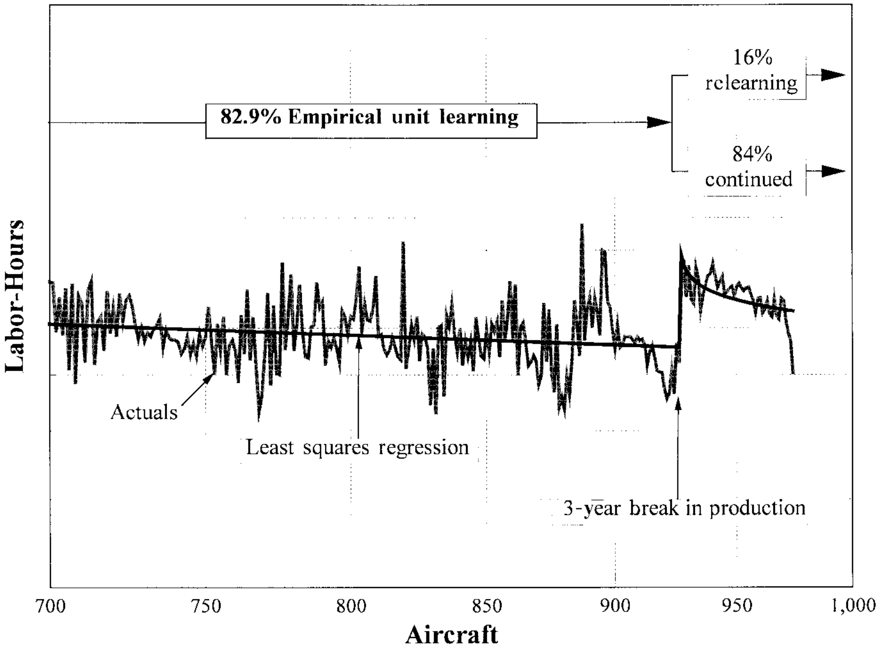

FIGURE 17.10.10 The effect of a break in production on learning.

Further study is obviously needed in this subject as the pace of technology development continues. It cannot simply be a case, for example, of looking for a correlation between engineering investment effort and the rate of learning, as ingenuity may reap greater rewards than sheer volume of effort or cost invested. However, in principle the concept of learning segmentation fits quite well with the contribution opportunity offered by various investments (i.e., the benefits are realized only if the investments are made).

Qualitative Argument: An Alternative to Empirical Evidence. There are circumstances where it may not be necessary or even possible to justify a hypothesis by statistical analysis. Qualitative argument may be an acceptable alternative in some cases.

Clearly, the potential cumulative savings on a learning curve attributable to any investment activity decreases as the build quantity remaining reduces. Heuristically (Fig. 17.10.11), potential savings diminish rapidly beyond the three-quarter quantity point. It could be inferred from this diagram that beyond this point any learning requiring an investment is less likely to provide an acceptable return or payback. This argument is supported by the tendency for many unit learning curves to flatten out during the latter stages of a production run. However, it does not preclude future investment, nor does it deny the possibility of future inspiration, but the argument does reflect the pragmatism of real life.

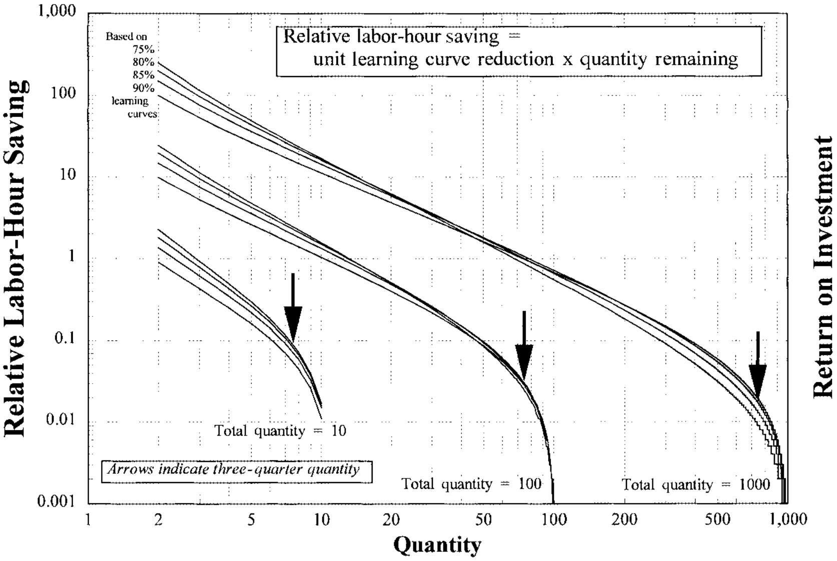

FIGURE 17.10.11 Potential cumulative learning curve savings.

IMPLEMENTATION OF CHANGES AND IMPROVEMENTS

The most difficult aspect of such a wide-ranging project is the limited access to relevant data. It is not the access to labor-hour data that is the problem; this is recorded and maintained to a very low level in accordance with U.K. MoD and U.S. DoD regulations. It is the access to data on the potential drivers that is problematic. Knowing if the data exists, and where to find it, is a major reason for involving a wider range of people in the process.

There were several potential drivers that could not be quantified readily because the historical data to support the analysis was not available. Critical component shortages or shortage levels is an example in question. It could be argued that there is little point in modeling data that cannot be forecast. (If you can forecast the shortage, why not prevent it!) However, if the analysis can be used to quantify a level of cost avoidance in support of a business case for an improved MRP system, for instance, then the analysis would be worthwhile. The level of design queries is another such example. The organization needs to address such issues and resolve the level at which it needs to maintain such data, and to what purpose.

RESULTS AND FUTURE ACTIONS

Segmented Learning Model

The evidence provided here is not conclusive, but it is encouraging, and more analysis is required. There is a need to model the effects and interactions of multiple drivers under different business conditions and scenarios in order to calibrate the model.

However, pragmatically, it would be difficult to calibrate a model, which captures the effects of all the potential causative factors at once. The engineer is urged to look for simplicity in the analysis stage, looking wherever possible for linear models, unless there is access to some robust nonlinear modeling package. It is advised that model development should be taken in stages, adding complexity only when there is a reasonable understanding of the constituent elements. However, an element of subjective judgement is likely to remain always, but it must be the aim to base this subjectivity on sound principles and logic.

Continuity of Learning

The current author is of the view that learning will continue for as long as there are enablers in place to allow it to continue; once these are removed, or exhausted, learning will truncate. The problem of predicting its eventuality remains.

The flexibility of the segmented model allows for either condition.

Footnote: Working with Cumulative Values

For all practical purposes, learning rates can be expected to be shallower than 50 percent. Within this range the unit learning curve is a diverging series (i.e., its summation diverges to infinity). The true cumulative total of a range of unit values from such a series, as might be required in estimating the value of a lot quantity, must be found by summation; there is no precise formula for the cumulative value. An estimate implies the acceptance of some error, and there are occasions in estimating when it is useful and quite acceptable to work with an approximation to the cumulative value. The asymptotic relationship of the unit curve to the cumulative average version does suggest that an acceptable approximation might be found. Conway and Schultz [4] offer the following relationship:

$$\text{Cumulative value, } C_A \simeq \frac{\mathrm{M}_1}{(\tau+1)}\left[(\mathrm{A}+0.5)^{\tau+1}-0.5^{\tau+1}\right]$$

The present author offers an alternative approximation formula:

$$\text{Cumulative value, } C_A \simeq \frac{\mathrm{M}_1}{(\tau+1)}(A^{\tau+1}-1)+\frac{\mathrm{M}_1}{2}(\mathrm{A}^{\tau}+1)$$

Neither relationship is valid for values of $\tau = -1$ (i.e., a learning rate equal to 50 percent). The principal difference between the two lies in the error term. The former always returns a positive error; the latter returns a negative error (Fig. 17.10.12). This property has some practical applications:

- Cost modeling across lot quantities is simplified.
- Learning curve trends can still be established even where batch-booking is a common practice, or the integrity of time bookings against individual units is called into question. Furthermore, it allows learning to be assessed where individual planeset bookings are not recorded, or the integrity of batch bookings only can be assured with any confidence.
- Incomplete units can be included on the basis of an equivalent aircraft completion.

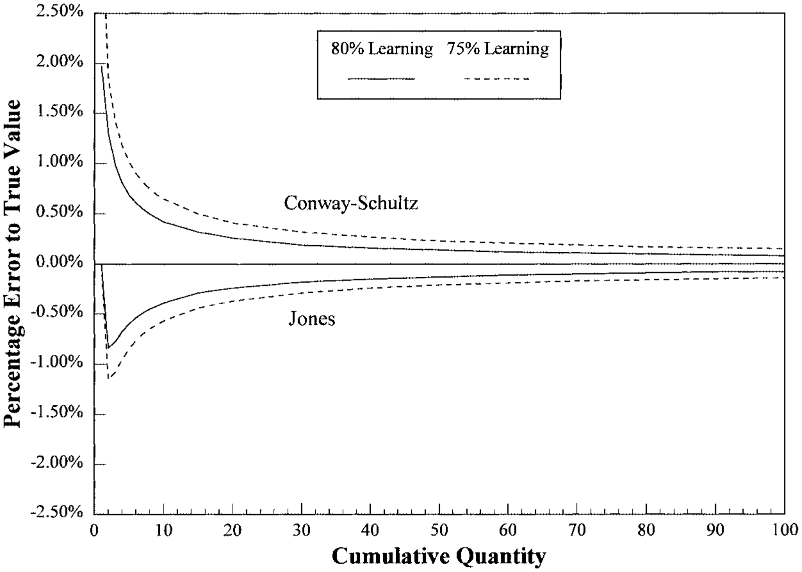

FIGURE 17.10.12 Cumulative value approximation errors.

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BIOGRAPHY

Alan Jones has a mathematics degree from the University of London, and a masters in business administration from Henley Management College in the U.K. He has worked with learning curves for over 20 years at BAE SYSTEMS (formerly British Aerospace) in a variety of roles including project engineer, industrial engineer, production estimator, and in business process development. During the 1980s he developed the concept of segmenting the learning curve as described in the case study and continues to use this approach.